MULTIPHASE GAS IN GALAXY HALOS: THE O VI LYMAN-LIMIT SYSTEM TOWARD J1009+0713*

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ABSTRACT

We have serendipitously detected a strong O VI-bearing Lyman-limit system (LLS) at \( z_{\text{abs}} = 0.3558 \) toward the quasi-stellar object (QSO) J1009+0713 (\( z_{\text{em}} = 0.456 \)) in our survey of low-redshift galaxy halos with the Hubble Space Telescope's (HST) Cosmic Origins Spectrograph. Its total rest-frame equivalent width of \( W_r = 835 \pm 49 \text{ mÅ} \) and column density of \( \log N(\text{O VI}) = 15.0 \) are the highest for an intervening absorber yet detected in any low-redshift QSO sightline, with absorption spanning at least four major kinematic component groups over 400 km s\(^{-1}\) in its rest frame. HST/Wide Field Camera 3 images of the galaxy field show that the absorber is associated with two galaxies lying at 14 and 46 kpc from the QSO line of sight. The absorber is kinematically complex and there are no less than nine individual Mg II components spanning 200 km s\(^{-1}\) in our Keck/HIRES optical data. The bulk of the absorbing gas traced by H I resides in two strong, blended component groups that possess a total \( \log N(\text{H I}) \simeq 18–18.8 \), but most of the O VI is associated with two outlying components with \( \log N(\text{H I}) = 14.8 \) and 16.5. The ion ratios and column densities of C, N, O, Mg, Si, S, and Fe, except the O VI, can be accommodated into a simple photoionization model in which diffuse, low-metallicity halo gas is exposed to a photoionizing field from stars in the nearby galaxies that propagates into the halo at 10% efficiency. In this model, the clouds have neutral fractions of 1%–10% and total hydrogen column densities of \( \log N(\text{H I}) \simeq 19.5 \). Direct measurement of the gas metallicity is precluded by saturation of the main components of H I, but we constrain the metallicity firmly within the range 0.1–1 \( Z_\odot \), and photoionization modeling indirectly indicates a subsolar metallicity of 0.05–0.5 \( Z_\odot \). This highly ionized, multiphase, possibly low-metallicity halo gas resembles gas with similar properties in the Milky Way halo and other low-redshift LLS, suggesting that at least some other galaxies have their star formation fueled by metal-poor gas accreting from the intergalactic medium and ionized by the stars in the host galaxy. As observed in the Milky Way high-velocity clouds, the strong detected O VI is not consistent with the photoionization scenario but is consistent with general picture in which which O VI arises in interface material surrounding the photoionized clouds or in a hotter, diffuse component of the halo. The appearance of strong O VI and nine Mg II components in this system, and our review of similar systems in the literature, offer some support to this “interface” picture of high-velocity O VI; the total strength of the O VI shows a positive correlation with the number of detected components in the low-ionization gas.

Key words: galaxies: formation – galaxies: halos – intergalactic medium – quasars: absorption lines

Online-only material: color figures

1. INTRODUCTION

A full understanding of how galaxies acquire their gas from the intergalactic medium (IGM) and return it there in the form of chemical and kinematic feedback will likely form an important part of any complete picture of galaxy formation. Motivated by questions of how galaxies obtain their observed stellar masses and morphology, theorists have developed a picture in which gas enters dark matter halos and galaxies by either cold flows along filaments (Keres et al. 2005), accretion of hot material that has passed through a shock on its way from the IGM (Dekel & Birnboim 2006), or in some complex, multiphase mixture of the two (Maller & Bullock 2004). Mass loss by feedback is driven in “superwind” outflows fueled by many correlated supernovae, by radiation pressure on dust (Murray et al. 2005), or in active-galactic-nucleus-triggered flows in those galaxies that possess active nuclei. Tidal or ram-pressure stripping of gas from satellite galaxies during gravitational encounters may also provide a gas supply to larger galaxies, or at least to their halos. All these gas processes may bear on such observational features of galaxies as their stellar masses, morphologies, and colors, but to be effective they must act across the 100 kpc scales of galaxy halos. Unfortunately the proposed accretion, feedback, and stripping processes are difficult to test directly because diffuse, ionized gas in the immediate vicinity of galaxies is difficult to detect. We therefore have an incomplete empirical picture of how accreting gas is distributed around galaxies of all types, what its temperature, density, and metallicity configurations look like, and how these features influence or are influenced by the host galaxy.

The classic quasar absorption-line technique provides a method for studying intergalactic and circumgalactic medium gas, even to very low density and metallicity. This technique

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has been used effectively to probe diffuse ionized gas in galaxy
halos, over long pathlengths through the IGM, and throughout
the halo of the Milky Way. The IGM samples reveal the statistical
correlations of galaxies with intervening absorbers, and in some
cases show physical properties of gas that is well within the
virial radius. However, most such information comes from post-
facto galaxy surveys that do not uniformly sample the range of
galaxy properties that may be related to the gas properties. While
extensive observational information exists about the quantity
and physical state of multiphase high-velocity cloud (HVC)
gas in the Milky Way halo (Sembach et al. 2003; Fox et al.
2005; Collins et al. 2005; Shull et al. 2009), and gas stripping
from dwarf galaxies is clearly demonstrated in the case of the
Magellanic Clouds and Stream, it is not known how typical the
Milky Way is in this regard.

To address the problem of how halo gas in other galaxies is
distributed and how it compares to the halo gas of the Milky
Way, we have begun an effort to systematically survey the
gaseous halos of low-redshift galaxies using the Cosmic Origins
Spectrograph (COS) aboard the Hubble Space Telescope (HST).
Our survey chose galaxies with sightlines to UV-bright quasi-
stellar objects (QSOs) passing through their halos, with redshifts
tuned to place the \( \lambda \lambda 1032,1038 \) doublet of O \( \text{VI} \) near the peak of
COS sensitivity at 1250–1350 Å. This survey design allows us
access to all the key far-UV ionization diagnostics from which
gas budgets, metallicities, and kinematics can be inferred. As
part of this survey we are also obtaining galaxy spectra and
high-resolution optical spectra of the QSOs. The main results
of this survey will be published elsewhere; here we report on
a serendipitous discovery from this program that nevertheless
addresses its main goal: to examine the gaseous fuel and/or
waste residing in galactic halos.

This paper reports new HST/COS and HST/Wide Field
Camera 3 (WFC3) and Keck HIRES and LRIS data for the
sightline to J1009+0713. This sightline exhibits a strong Lyman-
limit system (LLS) bearing a wide range of ionic absorption
from multiple ionization stages and in several distinct kinematic
components. The system was discovered serendipitously in
the data on this quasar obtained as part of our survey; the
absorption-line system associated with the targeted galaxy
along this sightline will be published separately. This paper
first describes the data collection and analysis for the HST/
COS and Keck/HIRES data on the sightline to the QSO, and
on our HST/WFC3 and Keck/LRIS data on the galaxies in
the field (Section 2). We then report the details of our line
identification and analysis (Section 3), and on the analysis of
the galaxy images and spectra (Section 4). Section 5 describes
physical models for the absorber. In Section 6, we describe
our general results and their significance for the larger picture
of gas in galaxy halos. We adopt the WMAP7 cosmological
parameters \( H_0 = 100h = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_\Lambda = 0.734, \text{ and } \Omega_m h^2 = 0.1334 \) (Komatsu et al. 2011).

2. OBSERVATIONS

2.1. COS Data

Data on the SDSSJ100902.06+071343.8 sightline (hereafter
J1009+0713) were obtained by COS over three orbits on
2010 March 29–30 as Visit 13 in Program GO11598. Two
exposures were obtained with the FUV G130M grating at
central wavelength settings 1291 and 1309, with total exposure
times of 1497 and 2191 s, respectively. Two exposures were
obtained with the FUV G160M grating at central wavelengths
settings 1577 and 1600, with exposure times of 2002 and
2007 s, respectively. All exposures were taken in TIME-TAG
readout mode with contemporaneous wavelength stim pulses
and the default FP-POS position. The data were processed with
the standard CALCOS data pipeline (v2.12) on retrieval from
the archive. More details on the performance of COS can be
found in the COS Instrument Handbook (Dixon et al. 2010) and
at the STScI Web site.

We began our analysis with the x1d files provided by
CALCOS. These extracted 1D spectra were then co-added to
combine the multiple exposures for each grating, and in turn
the two gratings, into a single spectrum. To align the four
exposures as closely as possible in wavelength space, small
(\(< 10 \text{ pixel} \) shifts were derived for each exposure individually
from the profiles of strong Galactic ISM absorption lines. This
co-addition was performed on the “gross counts” vector from
the CALCOS x1d files. The co-addition process sums counts
from separate exposures for each pixel, keeping track of the
effective exposure time for each pixel correctly. That is, if a
given pixel is ignored in a particular exposure because of data
quality flags, that exposure time is not summed for that pixel.
Thus we are effectively co-adding count rates rather than counts.

Co-addition in count space allows for a simple derivation of
the correct error vector in the Poisson limit of low total counts
(Gehrels 1986). The final co-added spectrum possesses a signal-
to-noise ratio \( S/N = 7–15 \) per resolution element. The resolving
power of COS is approximately \( R = \lambda/\Delta \lambda = 16–18,000 \)
over 1140–1750 Å, and the resolution element is sampled
by approximately six (analog) pixels in the 1D extraction.
We binned our final, co-added spectrum into 3-pixel bins for
analysis. This binning leaves approximately 2 bins per resolution
element, close to optimal sampling.

We note that the adopted version of CALCOS did not apply
a correction for fixed pattern noise, but that the co-addition
of exposures taken with different central wavelength settings
mitigates the regular shadowing pattern of the detector quantum-
efficiency (DQE) grid wires lying above the face of the COS
micro-channel plate detectors. During the co-addition of the
data we applied a correction for these grid wire shadows provided
to us by the COS instrument team. This correction removes
the grid-wire features, which otherwise result in \(< 15\% \) less
counts recorded over a few pixels and can mimic absorption
lines.

The final, reduced COS data appear in Figure 1. The spectrum
reveals at least two absorption line systems of significance
along this sightline. First, we discovered the \( z_{\text{abs}} = 0.356 \)
LLS that is the main focus of this paper. This system presents
an obvious Lyman-limit break at 1240 Å and a host of other
multiphase ionization stages that will be analyzed below. A
damped-Ly\( \alpha \) system (DLA) was discovered at \( z_{\text{abs}} = 0.114 \)
and has been analyzed by Meiring et al. (2011a). Both of these latter
systems were serendipitous discoveries along a sightline that
was selected to pass through the halo of an unrelated galaxy at
\( z < 0.25 \), and we have no reason to suspect that the selection of
the QSO itself or the targeted galaxy introduced a bias in favor
of these two extraordinary intervening systems. The properties
of the targeted galaxy and its associated absorber will be
presented as part of the main survey.

2.2. WFC3 Data

Based on the Sloan Digital Sky Survey (SDSS) images,
we identified two galaxies that could be associated with the
LLS at \( z = 0.356 \) and/or the DLA at \( z = 0.114 \). These are
Figure 1. Co-added COS data, plotted vs. observed wavelength, and binned by three raw COS pixels to optimal sampling of two bins per resolution element. The LLS analyzed in this paper and the DLA from Meiring et al. (2011a) are marked at the positions of Lyman series lines (green), metal lines (blue), and O vi (red). The Lyman limit of the present system is clearly visible as a complete absorption of the QSO spectrum at $\sim$1240 Å. Geocoronal Lyα emission has been excised near 1216 Å. The solid and dashed curves mark the opacity of the LLS using total column densities of log $N$(H i) = 17.8 and 18.0, respectively, as described in Section 3.5. (A color version of this figure is available in the online journal.)

Figure 2. Galaxy field, aligned with north at top and east to the left. The SDSS Skyserver image and our WFC3 image are shown for contrast. The larger panels are approximately 25 arcsec across. Galaxies 170_9 and 86_4 are at $z = 0.356$, the redshift of the LLS. At the redshift of the system, the 5" range bar subtends 25 $h^{-1}$ kpc. Precise impact parameters for the galaxies are given in Table 2. The insets show zoomed images of the three galaxies of interest and the QSO itself. (A color version of this figure is available in the online journal.)

labeled “80_5+86_4” and “170_9” in Figure 2 (left panel).6 The indistinct profile near the QSO is partially hidden from view by the ground-based point-spread function (PSF) of J1009+0713 in the SDSS image. Any attempt to relate the LLS to the galaxy properties, or even to obtain an accurate measurement of the impact parameter of this galaxy to the QSO sightline, was significantly hindered by this source confusion. In an attempt to conclusively identify the LLS-associated galaxies and to possibly discover a DLA host galaxy close to the sightline (fully within the SDSS PSF of J1009+0713), we obtained an image of this field with the WFC 3 aboard HST.

The WFC3/UVIS data on this field were obtained on 2010 June 24 as Visit 44 in program GO11598. We obtained images in two broadband filters, F390W and F625W. The QSO was placed at the “UVIS1” aperture position, and the WFC3–UVIS–MOS–DITH–LINE dither pattern was used with an exposure time of 376 s in F625W and 395 s in F390W. This pattern resulted in total exposure times of 2256 s and 2370 s in F625W and F390W, respectively. The six individual exposures in each filter were first processed by the default CALWFC3 pipeline. Each exposure then had the QSO subtracted off using a TinyTim model of the telescope PSF before the six exposures were added together using MultiDrizzle. More details about the processing of the WFC3 image can be found in the paper by Meiring et al. (2011a).

Even without co-addition or QSO PSF subtraction, the WFC3 image revealed that the candidate galaxy nearest the QSO in the SDSS image resolves into two galaxies, labeled 80_5 and 86_4 in Figure 2, that are separated by only $\sim$1". The image itself does not tell us whether one or more of these galaxies is associated with the DLA or LLS. We have attempted to constrain their redshifts separately with followup LRIS data, as described in the following section.

2.3. Keck LRIS

After the COS data revealed two unexpected and interesting absorbers in this sightline, we re-examined the imaging data from which we had selected the target QSO. To determine which of these galaxies, if any, were associated with our newly detected absorbers, we obtained 1"-wide longslit spectra of these two galaxy candidates with the Keck/Low-Resolution Imaging Spectrometer (LRIS) on 2010 April 5. These LRIS data were taken using the D560 dichroic with the 600/4000 l mm$^{-1}$ grism (blue side) and 600/7500 l mm$^{-1}$ grating (red side) which gives a spectral coverage between 3000 and 5500 Å (blue side), and 5600 and 8200 Å (red side). On the blue side, binning the data 2 x 2 resulted in a dispersion of 1.2 Å per pixel and an FWHM resolution of $\sim$280 km s$^{-1}$. On the red side, the data were binned 1 x 2, resulting in a dispersion of 2.3 Å per pixel and an FWHM resolution of $\sim$200 km s$^{-1}$. Exposure times were 800 s in the blue and 2 x 360 s in the red, which resulted in S/Ns of at least 3 per pixel for strong nebular emission lines in the galaxy spectra.

Data reduction and calibration were carried out using the LowRedux$^7$ IDL software package, which includes flat fielding to correct for pixel-to-pixel response variations and larger scale

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6 We label our galaxies with a position angle and angular separation in arcseconds with respect to the target QSO; thus, galaxy 170_9 has position angle of 170° (N through E) and is separated by 9" from J1009+0713.

7 http://www.ucolick.org/~xavier/LowRedux/index.html
illumination variations, wavelength calibration, sky subtraction, and flux calibration using the spectrophotometric standard star G191B2B. Precise and accurate systemic redshifts were obtained for both galaxies using a modified version of the SDSS IDL code “zfnd,” which works by fitting smoothed template SDSS eigenspectra to the galaxy emission-line spectra on both red and blue sides. The resultant weighted-mean redshift for 170_9 is \( z = 0.355687 \pm 0.00001 \). The long slit used to obtain this first set of Keck/LRIS observations was oriented to run from galaxy 170_9 through the midpoint of the faint profile seen for 80_5+86_4 in the SDSS image (the WFC3 image was not yet available). The slit was 1'' wide, so the recorded spectrum most likely includes contributions from both galaxies 80_5 and 86_4. For this spectrum, we obtain \( z = 0.355574 \pm 0.00002 \), with error bars calculated from statistical noise only. 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To account for systematic uncertainties in the absolute wavelength calibration, error bars calculated from statistical noise only.
Table 1
Measured Component Column Densities in the z = 0.3558 System

| Line | Centroid A (−95 km s⁻¹) | B (−10 km s⁻¹) | C (+60 km s⁻¹) | D (+180 km s⁻¹) |
|------|-------------------------|----------------|----------------|-----------------|
| Range | −200 to −65 | −65 to 30 | 30 to 130 | 130 to 250 |

**Notes.** All column density measurements were obtained via direct integration of the line profiles over the given velocity ranges, except where fitted parameters for column density, velocity, and Doppler b appear in the entry for that component. Upper limits for UV lines are obtained as 2σ limits by direct integration of the apparent column densities over the stated component velocity ranges. For multiplets, the limits use the strongest uncontaminated transition. Line profile fitting results are given as a triplet; column density, velocity centroid, Doppler b value.

- a Part of the definition of this component; H1 where possible, metal lines where necessary.
- b Subject to mild saturation.
- c Strongly saturated and/or line black absorption. The equivalent widths over each velocity range are converted to column densities assuming a linear curve of growth, which yield robust lower limits.
- d N II λ989.80 column densities are uncertain because they are blended with Si III λ989.87 to an unknown degree. These column densities should be treated as upper limits. Component D is even more uncertain, because it appears to be blended with other unidentified absorption.
- Contaminated by unknown absorption—no measurement or limit is possible.
- e Very noisy.
- f Si II λ1206 is contaminated and λ1253 and λ1250 are undetected. The λ1253 line provides the best upper limits.

Lyman lines in the outlying components, where profile fits were used.

Table 1
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Figure 4. Metal absorption lines from the $z = 0.3558$ LLS. Vertical dashed lines mark the centroid velocities of components A–D. Transitions are ordered by atomic element and, within that, by increasing ionization potential. The points with error bars at the top mark the measured velocities of the two associated galaxies with 25 km s$^{-1}$ uncertainty.

The line profile fits use a custom Voigt-profile fitting software that attempts to optimize a model of the line column densities, Doppler $b$ parameters, and velocities for an arbitrary input set of lines and atomic data, by minimizing the $\chi^2$. This code was first used to analyze the PG1211+143 sightline by Tumlinson et al. (2005). This software first constructs intrinsic line profiles and then convolves these with the appropriate non-Gaussian COS line-spread function (LSF) as described by Ghavamian et al. (2009) and available on the STScI COS Web site. These tabulated LSFs are specified for 50 Å intervals through the range...
Figure 5. Kinematic structure in apparent column densities (Savage & Sembach 1991) for low ions and O vi. Major components A, B, and C are broken down further according to their appearance in the Mg ii and Fe ii data obtained by HIRES. Note the wide range of apparent column density ratios between the low ions and O vi, particularly in components A and D. Flat tops arise from the truncation of the flux at 0.01 in the normalized data to avoid unphysical values of noise in the data, the \(\lambda\)1032 and \(\lambda\)1038 profiles agree well after it has been converted into apparent column densities using the method of Savage & Sembach (1991). Accounting for a modest degree of noise in the data, the \(\lambda\)1032 and \(\lambda\)1038 profiles agree well over the full velocity range, supporting the case that all this absorption is truly O vi, and that it covers the full kinematic range of absorption by the other detected ionization stages. While component groups A and D appear distinctly in the O vi profiles, B and C are not clearly separated; they are both blended together and possibly too broad to show individual peaks in the column density plot (Figure 5). We conclude that O vi is associated with all four identified component groups in this system.

Another notable feature of the O vi is its relationship to the neutral and low-ionization gas in the various components. In component A, strong O vi at \(\log N(O\ vi) = 14.6\) coincides with strong C ii, N iii, and Si iii, but also Mg ii and C ii. In components B and C, somewhat weaker O vi is associated with much stronger low ions, such as C ii, Mg ii, Si ii, and Fe ii. In component D, only H i, C ii, N iii, Si iii, and O vi are detected, with no corresponding Mg ii. Clearly the state of ionization varies across the absorber, which has an intrinsically multiphase structure.

3.5. H i Solution

With the four components defined either by their H i or metal-line profiles (see notes to Table 1), we can now derive a solution finding suggests that there may be further component structure in the H i and metal lines that we cannot resolve at the \(R = 18,000\) resolution of COS. In what follows, we analyze the major component groups as coherent objects with the proviso that they may in fact consist of subcomponents below the level of our spectral resolution.

### 3.3. Metal Lines and Ionization

The COS data on the LLS reveal absorption from a wide range of ionization stages, as shown in Figure 4. We detect absorption by C, N, O, Mg, Ca, Si, S, and Fe in the COS and/or HIRES data, and in ionization stages from Mg ii to O vi. However, the overall impression is of an absorption-line system that possesses a high degree of ionization. The species Mg i and O i are the only neutral atoms that are convincingly detected; Ca ii is usually detected in mostly neutral gas but is very weak here. Limits are placed on the neutrals of C, N, Si, and Fe. By contrast, strong absorption is detected in C iii, N iii, Si iii, and Fe iii. Our COS data do not cover C iv or Si iv, but N v \(\lambda\lambda 1238, 1242\), typically weak, is not detected in the \(S/N \sim 5\) data at that wavelength. These detections and limits, apart from any detailed analysis, point to gas that is substantially ionized in all components.
for the H\textsubscript{i} column densities in this absorber. Components A and D both appear in three or four higher Lyman series profiles, and can be profile-fitted directly. However, both B and C are strongly saturated and blended together, so simple line-profile fitting cannot disentangle them and measure their column densities without additional assumptions. The two straightforward components are taken up first. All relative velocities are given with respect to the adopted systemic redshift of \(z_{\text{abs}} = 0.3558\).

**Component A.** This component is defined at \(-95 \text{ km s}^{-1}\) by Ly\(\alpha\), where it appears distinctly but is blended with the blue wing of component B. It appears to be contaminated with unrelated absorption at Ly\(\beta\). Profile fits to Ly\(\alpha\), Ly\(\beta\), and \(\kappa\) were attempted, with the results appearing in Table 1. Consistent results are obtained with log \(N(H\text{i}) = 16.42 \pm 0.08\), \(b = 20 \pm 3 \text{ km s}^{-1}\), at \(-94 \pm 1 \text{ km s}^{-1}\). These values are adopted for further analysis.

**Component D.** This component is defined at \(+180 \text{ km s}^{-1}\) by Ly\(\beta\), Ly\(\gamma\), and perhaps \(\delta\). It is inseparably blended with component C of Ly\(\alpha\), contaminated at Ly\(\epsilon\), and absent in higher Lyman series lines. Only Ly\(\beta\) and Ly\(\gamma\) give acceptable fits, with log \(N(H\text{i}) = 14.8\), \(b = 16 \pm 3 \text{ km s}^{-1}\) at 180 \text{ km s}^{-1}. This fit is adopted for further analysis.

**Components B and C.** These two components are both strongly saturated and severely blended with one another at a velocity separation of 60–80 \text{ km s}^{-1} (as shown by their metal lines). Because of this blending and saturation we cannot, even in principle, fit them and constrain their column densities separately. Instead, we attempt to impose firm limits on the total \(N(H\text{i})\), based on the Lyman-limit opacity and observed Lyman series line profiles.

A firm lower limit to the total \(N(H\text{i})\) comes from the observed Lyman-limit opacity. For closely spaced components, this limit is insensitive to the separations and column density ratios and traces mainly the total column density of H\text{i}. We display two limiting cases in Figure 1. We adopt the Lyman continuum opacity as function of wavelength given by Osterbrock (1989). The red solid curve shows log \(N(H\text{i}) = 17.8\), which leaves \(-5\%\) transmission across the detected range of the LLS. By log \(N(H\text{i}) = 18.0\), the transmission is no longer visible and matches the absence of source flux in this region of the spectrum; higher column densities are also consistent with the data. We therefore regard log \(N(H\text{i}) = 17.8\) as a firm, conservative lower limit to the total column density of the LLS. Given the Lyman-limit opacity, 17.8 seems to have a low probability, so we also adopt a slightly higher value of log \(N(H\text{i})\) to bound the lower end of a 95\% confidence interval.

Upper limits to total \(N(H\text{i})\) come from the absence of damping wings from the Ly\(\alpha\) profile of the LLS. This limit is somewhat less firm than the limit from continuum opacity, since it varies slightly with the line broadening and number of components. Two identical components at the positions of the B and C components with \(b = 20 \text{ km s}^{-1}\) and log \(N(H\text{i}) = 18.5\) show damping wings that are only marginally consistent with the data (Figure 6). When each component is increased to log \(N(H\text{i}) = 18.7\) (for a total of 19.0), the damping wings are clearly excluded by the data. These profiles and limits strictly depend on the number of assumed components, which we can infer from the HIRES data. If we assume components at each of the three strongest Mg\textsubscript{i} and Mg\textsubscript{ii} components observed in the HIRES optical data, which are likely to trace the majority of the total H\text{i}, we find that by a total of log \(N(H\text{i}) = 18.5\), the damping wings appear, and higher values are increasingly poor fits. This is consistent with the two-component analysis. As the number of assumed components within the inner 80 \text{ km s}^{-1} increases, the column density per component increases. By log \(N(H\text{i}) = 19\), no tuning of \(b\) and number of components (even one) can hide the damping wings, so we regard this value as a firm upper limit to the total \(N(H\text{i})\). The weak presence of damping wings at a total log \(N(H\text{i}) = 18.8\) suggest that the value is likely to be lower than that, so we adopt this as an upper bound to a 95\% confidence interval. For further analysis, we adopt at 95\% confidence interval of log \(N(H\text{i}) = 18.0–18.8\), with a flat probability density within that range, since we have no information about which values in this range are more likely.

### 4. Metallicities and Star Formation of the Nearby Galaxies

The Keck/LRIS and WFC3/UVIS data on the galaxies in the field provide useful information about their redshift, luminosity, star formation rate, and metallicity. The reduced Keck/LRIS spectra appear in Figure 7 and the calibrated and PSF-subtracted images appear in Figure 2.

At \(z = 0.3558\), [O II] \(\lambda\lambda 3727, 3729\), H\(\beta\), and [O III] \(\lambda\lambda 4959, 5007\) are readily detected. The strengths of these emission lines, with appropriate corrections, provide constraints on the star formation rate and metallicity of the galaxies (Levesque et al. 2010). Accordingly, the accuracy of these quantities depends upon the accuracy of the relative emission line strengths and on the degree to which the flux calibration of the spectra is “absolute.” We therefore try to ensure that the flux calibrations of the blue and red sides of the LRRS spectra are consistent with each other, and attempt to correct for light losses in the 1’ slit by comparing our spectra with SDSS photometry if it is available for our galaxies. We accomplish this absolute flux correction by convolving the LRRS spectra with SDSS \textit{ugriz} filters (see Da Silva et al. 2011 for a description of the IDL code “spec2mag”) and comparing the observed spectral apparent magnitudes with the SDSS catalog apparent magnitudes (see J. K. Werk et al. 2011, in preparation, for details).

Only galaxy 170.9 has available SDSS photometry that enables us to perform an absolute flux correction. We do not...
correct the spectral fluxes of objects 80.5 and 86.4 since they do not have SDSS photometry (they are not even detected as one galaxy). The resultant corrective flux for 170_9 is 1.58 (0.494 mag in the g band) on the blue side and 1.65 (0.543 mag in the i band) on the red side. Since we have ugriz photometry available to us for object 170_9, we are able to use the IDL-code kcorrect (Blanton & Roweis 2007, v4_2) to obtain an estimate of its stellar mass, approximately $5.5 \times 10^9 M_\odot$.

We estimate the SFR from the Hβ emission line flux using the calibration of Calzetti et al. (2010), such that SFR (Hβ) = SFR (Hα) / 2.86, where SFR (Hα) ($M_\odot$ yr$^{-1}$) = 5.45 $\times 10^{-42} L$(Hα) erg s$^{-1}$. The factor of 2.86 represents the intrinsic ratio of Hα to Hβ for case B recombination at an effective temperature of 10,000 K and electron density of 100 cm$^{-3}$ (Hummer & Storey 1987). The SFRs appear in Table 2. For 86.4, the SFR is a formal lower limit, since we assume there was significant light loss from using a 1′′ slit (on the order of $\sim 38\%$). The errors given in the table account for only the rms of the line measurements; the flux calibration uncertainty, read noise, sky noise, and flat-fielding errors, are approximately $\sim 1\%$ for the emission lines in 170_9 and $\sim 7\%$ for the lower S/N emission lines in 86.4.

![Figure 7. Keck/LRIS spectra of galaxies in the field for 86.4 (top), and 170.9 (bottom). The break in the wavelength range is placed to avoid LRIS dichroic near 5500 Å. Detected emission lines are labeled. The red and blue sides for 86.4 are not normalized as they are for 170.9 (see Section 2.3).](image)

We obtain the nebular oxygen abundances for galaxies 86.4 and 170.9 using the strong line R23 method originally presented by Pagel et al. (1979), according to the calibration of McGaugh (1991). R23 is defined as $\log \left( \frac{[\text{O}II] \lambda \lambda 3727 + [\text{O}III] \lambda 4959 + [\text{O}III] \lambda 5007}{H\beta} \right)$. The drawbacks of the R23 method include a well-known degeneracy and turnover at $\sim 0.3 Z_\odot$ and large systematic errors on the order of 0.25 dex due to age effects and stellar distributions (Ercolano et al. 2007). To correct the emission lines for foreground reddening, we use a reddening function normalized at Hβ from the Galactic reddening law of Cardelli et al. (1989) assuming $R_V = A_V/E(B-V) = 3.1$, and using an $E(B-V)$ value of 0.013 (Schlegel et al. 1998). We cannot break the R23 degeneracy using any of the known methods (e.g., [N II]/[O II]) because our LRIS data do not cover lines redward of $\sim 6500$ Å in the rest frame of the galaxies. The upper and lower branch metallicities are presented in Table 2. Based on the well-known mass–metallicity relation of galaxies ( Tremonti et al. 2004), it is reasonable to assume the upper-branch metallicity for 170_9 given its estimated stellar mass of $5.5 \times 10^9 M_\odot$. The upper branch value is consistent with solar metallicity according to the updated solar oxygen abundance of $12 + \log(O/H) = 8.69$ (Allende Prieto et al. 2001; Asplund et al. 2009). The spectrum of 86.4 indicates a slightly lower upper-branch metallicity than the brighter galaxy 170_9, but given the errors in the measurements, all the upper branch measurements are consistent with solar metallicity and with one another.

As described below, we unfortunately have no direct measurement of the gas metallicity in the strongest components of the LLS. However, the indirectly indicated metallicity from photoionization modeling is $Z = 0.05$–$0.5 Z_\odot$. If this is correct, the gas would appear to have a low metallicity with respect to the galaxies and would favor an explanation in which the gas has entered this system from some other source—the IGM or a stripped dwarf galaxy. However, given the uncertainty in the metallicity of the strong LLS components, and the upper/ lower branch ambiguity for the galaxies, we cannot draw firm conclusions from this metallicity comparison.

### 5. PHYSICAL MODELING AND INTERPRETATION

In this section, we move from measuring column densities and kinematics to interpreting these quantities in terms of physical models, focusing on what we can learn about the ionization,
metallicity, and total gas budgets in these components from the detected absorption. From the detections of the various ionization stages of C, N, O, Mg, S, Si, and Fe alone, it is evident that at least some of the gas in this absorber possesses a high degree of ionization, even in the higher column density component groups B and C. These two components exhibit absorption in the second ions of C, N, S, Si, and Fe, the third ion of O vi, and relatively little absorption from the neutrals and first ions of these elements. Apart from any detailed modeling of ionization, the ratios N ii/N i and Fe iii/Fe ii indicate a significant ionization fraction. The solid detection of O vi in all components further indicates a highly ionized fraction of the gas, whether or not it arises from the same ionization mechanism as the lower ions.

To estimate the degree of ionization in the absorbing clouds and from that the total budget of gas that has been detected, we produced photoionization models with the Cloudy modeling code (version 08.00) last described by Ferland et al. (1998). This effort is hindered by several limitations that must be acknowledged at the outset. Photoionization models described by a density, ionization parameter, incident spectrum, metallicity, and total gas content require a larger number of uncertain parameters than are formally constrained by the data, so any results must be considered indicative rather than conclusive. The shape and orientation of the absorbing cloud with respect to the nearby galaxies and to the observer are both unknown; we can only assume the simplest cases. While these two factors are generic to absorption systems in QSO sightlines, this particular system presents two additional features that complicate modeling. Its two strongest components, labeled B and C, are inseparably blended with one another in all available lines of H i, so models are not robustly constrained as usual by a definite N(H i); we have only a loose constraint on the sum of the neutral hydrogen column in B and C (see Section 3.5). Furthermore, many of the most important lines of intermediate ions, such as C ii and Si ii, are strongly saturated and blended across all the component groups.

With these caveats in mind, we model the absorbing clouds with a single plane-parallel slab model illuminated on one side by a uniform incident radiation field. The model field uses two components. First, we attempted models with the composite extragalactic radiation field of Haardt & Madau (HM05, as implemented within Cloudy). This spectrum yields $\Phi_{\text{HM}} = 3.2 \times 10^5$ photons cm$^{-1}$ s$^{-1}$ for $>1$ Ryd photons at each point in space. By itself, the composite HM field generally fails to achieve the observed ratios of second to first ions of C, N, O, Si, and Fe until the ionization parameter is increased by a low density and the clouds are more than 1 Mpc in size, too large to reside in galaxy halos. It is perhaps not surprising that this spectrum fails, since it represents the average ionizing background of all galaxies and QSOs as transmitted by the IGM. But our absorbers are not located at a random point in space, but within 15–50 kpc of galaxies with star formation rates of $\sim 0.2–2$ $M_{\odot}$ yr$^{-1}$. Models of the Milky Way halo that attempt to account for the ionization of the Galactic HVCs typically find that the Milky Way may contribute $10^5$ ionizing photons cm$^{-2}$ s$^{-1}$ even $\sim 100$ kpc into the halo in the direction normal to the disk (Bland-Hawthorn & Maloney 1999b, 1999a; Fox et al. 2005), and nearly $10^6$ photons cm$^{-2}$ s$^{-1}$ at 40 kpc.$^{10}$ This flux exceeds the contribution of $\Phi_{\text{HM}}$ by a significant margin. Thus, even a modest degree of star formation, if its UV radiation propagates efficiently into the halo, can exceed the extragalactic background at physical separations like those observed in the present system.

We therefore add in a second ionizing field component, modeled as a galaxy undergoing a recent episode of star formation, drawn from the Starburst99 libraries (Leitherer et al. 1999) and corresponding to a continuous star formation history over 10 Myr with a Salpeter IMF from 1–100 $M_{\odot}$ and solar metallicity (the ionizing photon output at 0.5 $Z_{\odot}$ is only 15% higher). For a star formation history extending far into the past, the instantaneous spectrum reaches a steady state beyond a few million years and changes negligibly with the assumed age. The galaxy metallicities (see Section 4) suggest that we should adopt $Z_{\odot}$ for the starburst. This spectrum generates a total of $Q_* = 10^{53.14}$ (SFR/$M_{\odot}$ yr$^{-1}$) ionizing photons s$^{-1}$. We assume that a uniform, wavelength-independent fraction $f_{\text{esc}}$ of these ionizing photons escape the ISM of the galaxy to illuminate material in the halo. At a distance $d$ in kpc, this ionizing field will impart to a cloud of uniform density $n_H$ a field characterized by the dimensionless ionization parameter $U$:

$$U = \frac{1}{cn_H} \left( \frac{Q_* f_{\text{esc}}}{4\pi d^2} + \Phi_{\text{HM}} \right) = \frac{0.01 \text{ cm}^{-3}}{n_H} \left[ 10^{-3} \frac{\text{SFR}}{M_{\odot} \text{ yr}^{-1}} f_{\text{esc}} \left( \frac{20 \text{ kpc}}{d} \right)^2 + 10^{-4} \right]$$

where in the final equation the quantities have been scaled to typical values for halo clouds. This relation does not account for radiative transfer in the Lyman continuum, and assumes normally incident radiation, and so it is only an approximation for real clouds. For $d = 20$ kpc and SFR = 1 $M_{\odot}$ yr$^{-1}$, the ionization parameter $\log U \sim -3.3$. The constants $10^{-3}$ and $10^{-4}$ are convenient approximations good to better than 10%. In these typical conditions, the stellar ionizing flux exceeds the HM spectrum by an order of magnitude, consistent with results from the Milky Way. At all higher SFRs, higher $f_{\text{esc}}$, and lower distances, the stellar ionizing field is even more dominant. Since we do not know the cloud distance to the galaxy, the density, or the $f_{\text{esc}}$, we cannot use this relation to specify $U$ for a given absorber. However, once a photoionization model has been found and $U$ constrained by observations, along with SFR for the galaxies, we can use this relation to obtain estimates of the other parameters.

The sum of these HM05 and starburst radiation field components is normalized within Cloudy to achieve a specific ionization parameter at the face of the model cloud. The model clouds are calculated from their sharp illuminated face to a stopping column density of $N(\text{H i}) = 19.5$, to cover components B and C; these models are valid for any lower total $N(\text{H i})$ if their results are truncated at that column density so are applicable to A and D as well. The model clouds are assumed to have a uniform metallicity of appropriately scaled solar relative abundances; models with total metallicity from solar to 1% solar were explored.

5.1. Components B and C

5.1.1. Metallicity

In components B and C, we detect weak absorption from neutral oxygen in two transitions: $\lambda 1302$ and $\lambda 988$. These lines are likely unsaturated, as the apparent column density

$^{10}$ These models are consistent with the $\text{H} \alpha$ emission from the HVCs (Weiner et al. 2002; Putman et al. 2003), but not the Magellanic Stream, which is hypothesized to have at least some of its gas ionized by shocks (Bland-Hawthorn et al. 2007).
profiles shown in Figure 5 (middle panel) are consistent in the strong component groups B and C. The B component of the λ1302 line appears mildly contaminated; we adopt the value \( \log N(O\text{I}) = 14.5 \pm 0.2 \), boosting the error from 0.1 to 0.2 dex to account for the uncertainty in the contamination. For component C, we obtain consistent measurements from both lines, \( \log N(O\text{I}) = 14.2 \pm 0.2 \). Significant absorption is not detected in components A or D, and direct integrations over their velocity ranges yield upper limits of \( \log N(O\text{I}) < 13.9 \) (2\(\sigma\)).

Neutral oxygen is a useful metallicity indicator in moderately ionized gas, since its ionization potential of 13.6 eV and charge exchange reactions with H lock its ionization fraction to that of hydrogen in typical conditions. Unfortunately these well-detected OI lines must be compared to a highly uncertain total H I column, ranging anywhere from \( \log N(H\text{I}) = 18.0–18.8 \) (95% confidence). With this range, metallicities from solar oxygen abundance \( 12 + \log(O/H) = 8.69 \) (Allende Prieto et al. 2001; Asplund et al. 2009). We therefore cannot obtain a robust, direct measurement of gas metallicity in this system, owing to the systematic error in \( \log N(H\text{I}) \) introduced by the strong saturation and blending of the two inner components. However, we can impose upper and lower limits, \( Z = 0.15–1.0 Z_\odot \) based on the 95% confidence range derived for \( N(H\text{I}) \) above (or \( Z = 0.1–1.6 Z_\odot \) with the firm limits on \( N(H\text{I}) \)). This circumstance somewhat limits our ability to interpret this material as either infall or outflow from the associated galaxies. However, modeling of absorption from ionized gas indirectly indicates sub-solar metallicity, as shown in the following section.

5.1.2. Ionization

The results of our Cloudy photoionization model with this Starburst99 input spectrum appear in Figure 8, specifically for the parameters \( \log U = -3.5 \) and 10% solar metallicity in the gas. The left column of this figure shows the column density ratios of the key ions, and the right column shows the cumulative column densities, \( N(X) \), as a function of H I column density into the cloud (note that this is not physical depth, or total H column, which is proportional to depth for constant density). These quantities are plotted with respect to a varying \( N(H\text{I}) \) since we must account for the uncertain total H I column density. If that column density were well constrained by measurement, we could choose one vertical slice though this space with a fixed \( N(H\text{I}) \) and analyze models of varying \( U \) and \( Z \), as is typically done for photoionization models. Instead, we analyze these families of models with a range of \( N(H\text{I}) \) and proceed in two steps. First, we adjust the ionization parameter \( U \) to place the ion ratios in the left column within their permitted ranges. Then, holding \( U \) fixed, we vary the metallicity until the cumulative column densities in the right column fall into the observed ranges for themselves individually and also for H I. Where these curves lie inside the boxes that mark data, both the total \( N(X) \) and the \( N(H\text{I}) \) are reproduced by that particular model. Thus, the ion ratios constrain the ionization parameter while the column densities constrain the metallicity.

The model with \( \log U = -3.5 \) provides an acceptable fit to the ratios of the observed ions, except that it underproduces N III and produces essentially no O VI or S IV. However, the detected N III is likely contaminated by Si II or other absorption and so the observed ratio N III/N II is artificially high; we discount this ratio to discriminate models. Otherwise, these parameters are a good model for the components B and C. At the depth into the cloud at which this model has achieved \( N(H\text{I}) \simeq 18–18.8 \) the clouds are still predominantly ionized. As shown in Figure 8, the lower \( N(H\text{I}) \) models within the permitted range have lower neutral fractions, while the higher \( N(H\text{I}) \) have higher neutral fractions, so that the typical total \( N(H) \) range of these models is \( N(H) \simeq 19.5–20.0 \). Thus in models with pure photoionization, these clouds are nearly all ionized.

The column densities of well-measured ionization stages (right column) also indicate a subsolar metallicity. This constraint on the metallicity should be considered indirect, because it depends on the assumption of pure photoionization. Yet under this assumption, models with an ionization parameter, \( \log U \simeq -3.5 \), that matches the observed ratios of ions from the same element fail to match the column densities of all these ionization stages unless the metallicity is 5%–50%, as shown in Figure 8. This indirect measure of the gas metallicity is affected less by the saturation of H I than might be expected.

![Figure 8](https://example.com/figure8.png)

Figure 8. Photoionization modeling for the B and C velocity components of the LLS. This model assumes the Starburst99 spectrum described in the text with \( \log U = -3.5 \) and \( Z = 0.1 Z_\odot \). The left column shows column density ratios of key ions, while the right shows the cumulative column densities. Both are plotted with respect to cumulative \( N(H\text{I}) \). The ranges permitted by the data for column densities and ratios are marked, coded in color to match their model curve. In the right column, the species are color coded according to their stage of ionization, e.g., 1 equals C I in orange, 2 equals C II in blue. (A color version of this figure is available in the online journal.)
As shown in the right column of Figure 8, the column densities of the first and second ions increase slowly with respect to \(N(\text{H})\) through the range where it increases from 18.0 to 18.8, because over this range the H is becoming increasingly neutral and is added to the line integral through the cloud at a much higher rate, per pathlength, than species such as Mg II or Fe II for which the ionization fractions change little over this range. For a given \(U\), these cumulative column density curves shift up and down in those panels of the figure in direct proportion to the assumed cloud metallicity, which has been adjusted to best match the greatest number of column densities. The best fitting model has 0.1 \(Z_\odot\), but values from 0.05–0.5 \(Z_\odot\) still provide decent matches for most ions. Even though the metallicities estimated directly from the detection of O I are highly uncertain because of the saturation of the H I, they are consistent with these models at the higher end of the permitted range of \(N(\text{H})\).

Finally, we have assumed a nominal density of \(n_H = 0.01 \text{ cm}^{-3}\), which yields cloud sizes of 1–3 kpc. We therefore have a model in which the two strongest components in the LLS absorber are consistent with diffuse, possibly low-metallicity clouds of total gas column \(\log N \simeq 19–20\) and with kpc scale that are ionized by the stars in their nearby galaxies. These absorbers suggest that star-forming galaxies with \(f_{\text{esc}} = 0.1\) may be able to photoionize some of their own halo gas under the right conditions.

In light of the appearance of many ionization stages in this absorber, e.g., both O I and O VI, we must consider that some or all of the gas arises in warm or hot collisionally ionized material, such as might arise in a shock or conductive interface between hot and cold gas. For purely collisionally ionized gas without a photoionizing field, we can use individual ionization ratios to constrain the temperature. The ratios of the second ions to the first ions of C, N, Si, and Fe (e.g., N III to N II) all prefer a temperature of between 20000–80000 K. Over this range the neutral fraction of H drops from \(-0.1\) to \(-10^{-4}\), so if collisional ionization dominates in these absorbers, the total column density of H will exceed \(\log N(\text{H}) \simeq 19.5\) and could be substantially higher. However, the observed ratio of Mg II/Mg I = 1.8 dex prefers a temperature \(T < 20,000\) K, and is one of the better determined ratios in components B and C. Thus, no single temperature in CIE describes all the detections. By contrast, the photoionization model above appears to be able to account for these ratios altogether, with the significant exception of the O VI.

An important caveat to this modeling is that we have considered ionization mechanisms in isolation, rather than possible combinations of them. Such a model might explain the co-existence of Mg II and O VI, for instance, if the latter is collisionally produced while the former arises in a photoionized cloud. Such a model will require more parameters than either model on its own, but may be tenable. We will discuss the possible “multiphase” nature of the O VI absorber below.

Indeed it is impossible to reconcile O VI and low ions such as Mg I into the same CIE or photoionization model, and both of these appear in components B and C. Since the O VI is not readily reproduced by either of the photoionization models considered above, it probably does arise in collisionally ionized gas. If so, the corresponding H I may be too weak to separate from the stronger H I from the photoionized component. If the O VI exists at its peak ionization fraction \(f_{\text{OVVI}} = 0.2\) in CIE at \(T = 10^{5.5}\) K, the corresponding H I has \(N(\text{H}) \simeq (2.5/Z) \times 10^{12} \text{ cm}^{-2}\) where \(Z\) is the metallicity relative to solar (thus \(2.5 \times 10^{13} \text{ cm}^{-2}\) at 0.1 \(Z_\odot\)). Only if the assumed temperature drops to \(100,000\) K, \(f_{\text{OVVI}} \simeq 10^{-5}\), does the associated H I exceed \(10^{18} \text{ cm}^{-2}\) and so become comparable to the observed values. However, at this temperature the H neutral fraction is also \(\simeq 10^{-5}\) and the total H column is an implausibly large \(10^{23} \text{ cm}^{-2}\). We therefore conclude that a collisional origin for the O VI (and possibly other high ions for which we do not have coverage) is possible, and that the corresponding H I would go undetected under most circumstances. Such a case might occur if the O VI arises in the interface layer between a photoionized cloud and a hot, diffuse halo, as has been proposed for the HVC population of the Milky Way (Sembach et al. 2003; Fox et al. 2004). As these interfaces lie at intermediate temperatures between hot and cold material, they may account for some portion of the intermediate ionization stages as well. Were we able to account for this properly, it might change our conclusion about the photoionization models described above. However, these interface models typically produce less O VI than is observed, as discussed more below.

We are therefore forced to conclude that these components consist of complex multiphase material, and that they may arise from some combination of photoionization and collisional ionization. The essential point of these ionization modeling exercises is not that a particular model gives a perfect fit to the observed ion ratios; the uncertain \(N(\text{H})\), component blending, and line saturation ensure that no perfectly robust modeling is tenable. However, ionization models with a range of plausible conditions all point in the same direction; that the bulk of the gas traced by the H I and the metal-line absorption is highly ionized, with a total H column density exceeding that seen in \(\text{H}\) I by a factor of 10–100. There is still more highly ionized gas, traced by O VI in all the components, that may indicate interfaces between this photoionized halo gas and its environment. While we cannot completely rule out collisional ionization for the bulk of the strong components B and C, a photoionization model incorporating UV light from star-forming regions in the nearby galaxies appears plausible if the cloud has density \(n_H \simeq 10^{-2} \text{ cm}^{-3}\), lies 20–50 kpc from the associated galaxies, and if those galaxies propagate \(\sim 10\%\) of their ionizing photons into the halo.

5.2. Component A

This component exhibits a wide range of ionization stages, from Mg II to O VI. This range of species cannot be accommodated within a single photoionization or collisional ionization model, for the same reasons that applied to B and C above; it is clearly “multiphase.” Following the same procedure as above, we attempted to fit as many species as possible into a single model to estimate what properties the cloud might have under various physical scenarios.

We first ask whether the combination of a galactic star-forming spectrum with the diffuse extragalactic background will provide a suitable model, as it did for components B and C. Since we have a robust measurement for \(\log N(\text{H}) = 16.5\) in this case, we can restrict our attention to models that give that value. These results appear in Figure 9. Most regions of this parameter space with \(\log U \gtrsim -3\) (from the combination of the HM and S99 spectra) satisfy the lower limits on C III and Si III. The measured column densities of C II, Mg II, Si III, and S IV are constraining, and mutually consistent in a small region centered around the filled circle at \(\log U = -2, Z = 0.2 Z_\odot\). This model has a total H column of \(\log N(\text{H}) \simeq 19\), and thus a neutral fraction of only \(10^{-2.5}\). However, the ionization parameter is 10–30 times higher than for B and C, suggesting that this component has
some combination of lower density and/or proximity to the ionizing source. We therefore conclude that this photoionizing model is plausible for all the species except the O vi.

The O vi detection suggests that some of this gas may reside in a hotter, collisionally ionized component. We pursued this hypothesis by adjusting the temperature and metallicity of a purely collisionally ionized model cloud to achieve matches to the observed ratios and column densities. No single temperature is clearly indicated; the well-measured ratio of S iv to S iii is matched by a model with 80,000 K, but this model greatly underproduces both Mg ii and O vi, which has its highest ionization fraction at ~300,000 K. Single-temperature models that give O vi column densities above $10^{14}$ cm$^{-2}$ typically give Mg ii column densities 100 × lower than we measure here. A model with $\log T = 5.3$ gives a ratio of O vi to S iv that is near the observed value, but overpredicts the observed ratio of S iv to S iii. Where therefore conclude that no single-temperature collisional ionization model can explain the absorption by component A; distinct models are needed for the low ionization gas up to C iii, Si iii, and S iii, while a hotter, collisionally ionized phase could account for the O vi and possibly the S iv. In a combined model, the neutral H fraction associated with the collisional component is likely quite low with respect to the measured $\log N(H) = 16.5$, which would trace predominantly the photoionized component. We thus have no constraint on the metallicity of the hotter component.

Thus, we find that Component A can also be accommodated into a simple scenario in which low-metallicity gas in the halo(s) of the nearby galaxies is ionized by their star formation. Such a simple scenario can account for the observed column densities with the significant exception of the O vi, for which a collisionally ionized phase may be preferred.

5.3. Component D

Component D has a column density $\log N(H) = 14.8$, and exhibits strong absorption in O vi, saturated C iii and Si iii, and the problematic transition of N iii. Significantly, no Fe iii is seen here as in B and C. With fewer detected ions, models are more loosely constrained. In this case, a single temperature CIE model can account for the column densities of C iii, Si iii, N iii, and O vi in a narrow temperature range around $\log T \simeq 5.25$, provided the total H column density is $\log N(H) \sim 20$ and the metallicity is solar. However, this model conflicts with the observed Doppler parameter $b = 16$ km s$^{-1}$ obtained by consistent fits to the profiles of Lyβ and Lyγ. At $\log T = 5.3$, the Doppler parameter for H should be no less than $b = \sqrt{2kT/m_H} = 57$ km s$^{-1}$, but the line profiles prefer a value $T \lesssim 20,000$ K, which corresponds to $b = 16$ km s$^{-1}$. We therefore rule out a single CIE model for all the detected absorption in this component.

If we consider a photoionization model for this component, we find that the number of detected ions is generally insufficient to constrain the ionization parameter to the degree that was possible for A, B, and C. Any model with $\log U \gtrsim -2.5$ gives the correct column densities of C iii and Si iii, but tends to produce too much Mg ii, which is undetected, unless the metallicity is less than 0.3 solar. This region of parameter space is shown in Figure 10. The allowed area with $\log U = 2.5$ to $-1$ and below $\sim 25\%$–$40\%$ solar produces enough C iv and Si iv without producing too much Mg ii or S iv. The total gas column densities $N(H)$ range from $10^{19}$ to $10^{19.5}$ cm$^{-2}$ as $\log U$ increases from $-2.5$ to $-1$. This component would appear to have a very large ionization correction, with only 10$^{-3}$ or 10$^{-4}$ of the hydrogen in H i. As for the other components analyzed above, we find that the combined ionizing radiation can explain the detected absorption, but only if the gas is highly ionized and has a subsolar metallicity.

5.4. What Creates the O vi?

None of the analysis just presented answers convincingly the question of what creates the highly ionized gas traced by the O vi. Models with purely photoionized gas do not produce enough O vi, or if they do they do not also explain the lower-ionization gas. It is the coexistence of this strong O vi, together with the low ions, that make this absorber “multiphase.”

We must consider the possibility that the highly ionized gas in this system—the O vi and perhaps some or all of the S iv, S iii, and N iii—arise in non-equilibrium situations such as shocks, conductive interfaces between hot and cold material, or simply cooling gas which is out of thermal and/or ionization
equilibrium. Fox et al. (2004) and Indebetouw & Shull (2004a, 2004b) have compiled models for many of these phenomena, and mapped out their predicted column-density ratios in Si IV, C IV, N V, and O VI. Unfortunately our COS spectra have coverage of only the latter two ions, and N V is not detected. The ratio N(N VI)/N(O VI) provides only an upper limit for the four component groups, which ranges from $<-0.6\, \text{to} \,-1.0$. These limits provide no constraint, since they are consistent with shock ionization, radiative cooling, conductive interfaces, and turbulent mixing layers, as compiled by Fox et al. (2004). The uncertainty of comparing models to data in this fashion is complicated by the possibility that the gas under study has non-solar relative abundances of the diagnostic elements C, Si, N, and O, which allows the regions occupied by these various models to move within the column density ratio space. While Fox et al. (2004) are able to correct these abundance ratios based on independent measurements of relative abundances, we do not have that much constraint here. So we are unable to produce quantitative constraints on ionization mechanisms using this technique.

This absorber is notable not only for its very high total column density on O VI, but also for how it produces this high value. We do not see a monolithic, saturated component in O VI, thermally broadened into a single profile in hot gas, nor do we see O VI associated only with the strongest or weakest H I. Rather, we see a complex profile in which the O VI absorption is spread over nearly 400 km s$^{-1}$ and breaks into at least two and possibly more distinct components, which line up with components at similar velocities in lower ions. With a sightline that extends over $>100$ kpc through the halos of two galaxies, it seems natural to guess that the O VI arises in multiple distinct objects within the halo which may or may not be associated with the individual galaxies. Strong shocks ($v \sim 600$–2000 km s$^{-1}$) can exhibit column densities in the range of our detections (Gnat & Sternberg 2009), but imply post-shock temperatures of $T \sim 5 \times 10^{6}$ K and H I thermal linewidths $b \geq 70$ km s$^{-1}$. The strength and complex component structure of the H I lines precludes a search for such a broad component, which would only be detectable in the Lyα profile in this LLS. Thus, while we cannot rule out shocks for some of this O VI, we have no strong indication for them either. We note that some O VI absorbers reported in the literature have corresponding broad H I components that could indicate the expected temperature in shocked gas (Tripp et al. 2001; Richter et al. 2004; Narayanan et al. 2010; Savage et al. 2011).

One possible explanation for the observed kinematic and ionization pattern is that the O VI arises in transition layers between hot and cold gas, such as might occur for neutral or photoionized clumps falling through a Galactic halo and interacting with the hot halo gas left there by the formation of the galaxy. O VI is believed to trace interfaces between stable cold ($T \sim 10^{4}$ K) and hot ($T > 10^{6}$ K) phases of the ISM and circumgalactic medium because it achieves its maximum ionization fraction ($T \sim 100$–300,000 K) near the peak of the radiative cooling curve and so is short-lived. In this simple scenario, interfaces arise where cold clouds interact with the hot medium and are generally unrelated to, or weakly dependent upon, the size and/or quantity of gas in the cold clumps. Most simply there is just one interface per cloud, however large the cloud.

Quantitative models of conductive interfaces and turbulent mixing layers typically produce column densities of O VI in the range $10^{12}$–$10^{13}$ cm$^{-2}$, lower than we detect here (cf. Borkowski et al. 1990; Slavin et al. 1993; Indebetouw & Shull 2004a, 2004b; Gnat et al. 2010), and so multiple interfaces must be invoked. The models of Gnat et al. (2010) find that O VI column densities typically have N(O VI) $< 10^{13}$ for cold clouds bounded by conductive interfaces within a hot corona, so that $\sim 100$ interfaces are implied by the total column density of the J1009+0713 absorption-line system. A very large number of low-column density O VI components probably could be accommodated by our data, since blending and thermal broadening would likely make them difficult to distinguish from a smaller number of higher column density components, which is similar to what we observe.

However, the interface scenario implies a simple observational pattern: that O VI should appear whenever low ions trace colder clumps in the halo, and that the strength of O VI absorption near galaxies should increase with the number of detected components in the cooler material, and correlate with them in velocity space. The overall pattern observed so far is that the column density of O VI is relatively insensitive to the total N(H I) in surveys of IGM absorbers, though the patterns depend sensitively on the number of defined components, which vary from study to study especially for the strongest absorbers. The column density of O VI varies in our case by only about 0.2 dex across the four detected component groups, while the H I column density varies by at least three and possibly four orders of magnitude. This striking lack of correlation suggests that the presence and total quantity of O VI is not related directly to the total quantity of gas. Indeed, this is a generic pattern of O VI absorbers that has been noticed in systematic surveys (Danforth & Shull 2008; Tripp et al. 2008; Thom & Chen 2008). In the compilation of O VI absorbers by Thom & Chen (2008), N(O VI) varies by 1.5 dex over five decades of variation in N(H I). This is partly due to the dramatically multiphase character of some of the absorbers in the Thom & Chen sample, but even the “simple” O VI absorbers (systems with well-aligned O VI and H I components and simple component structure with no clear evidence of multiple phases) identified by Tripp et al. (2008) show this effect, with N(H I) varying by three orders of magnitude while N(O VI) only changes by 1 dex. Taken as a system, the J1009+0713 occupies the extreme upper right of this diagram, with log N(O VI) = 15.0 at log N(H I) $\sim 18.5$, but taken by components the four groupings scatter over the full range found by Thom & Chen (2008). Thus, the comparison of O VI to H I is roughly consistent with the interface scenario.

The low ion Mg II is another cold gas tracer that could provide information on the interface scenario. We have successfully built a photoionization scenario that works well for the detected Mg II and other low ions. The simplest interface scenario suggests that each “cold cloud” could contribute two interfaces to the sightline. We have grouped the major kinematic components in this absorber into four ranges, but if components are generously defined to maximize their number for the Mg II there could be approximately nine components over groups A–C, but none for group D. Thus at most 20 interfaces are expected in the O VI, not the $\geq 100$ that are implied by the observed column density and the interface models. While there could be numerous cold clouds and twice as many interfaces that fall below even the stringent detection limits of our HIRES data, there would need to be a large number of undetected Mg II to provide enough interfaces to reproduce the O VI.

The features of this system recall the properties of some other low-redshift, O VI-bearing LLS that have been intensively studied to which we can compare and contrast our results.
These systems are tabulated in Table 3, where we list all the systems in the literature with well-studied UV spectra covering O\vi from HST or FUSE and having \( \log N(\text{H}i) > 16 \) to within observational errors. The listed number of components is the number of H\,i and/or metal-line components given in the references cited. Here we have assigned nine components to the J1009+0713 LLS based on the number of observed Mg\,ii components in the HIRES data, which has comparable resolution to the STIS/E140M data used in most of the other cases from the literature. This compilation of results suggests two possible patterns of relevance to the J1009+0713 LLS and the origins of strong O\vi absorbers. First, the total quantity of O\vi is not well correlated with the column density of H\,i. The former spans less than one order of magnitude while the latter covers more than 3 dex. This poor correlation is one of the central puzzles in the origins of the O\vi absorbers (cf. Figure 6 of Thom & Chen 2008). Second, the total system column density of O\vi appears to correlate with the number of detected components in the system, such that >4 components gives \( \log N(\text{O} \, \text{vi}) > 14.5 \), while systems with a smaller number of components have lower column density. This effect is clearly seen in Figure 11, where we plot the O\vi column density over the number of components from Table 3.

While the sample is still small, there is a marked correlation that is well outside the typical error on individual measurements (conservatively assigned as \( \pm 0.1 \) dex and shown at lower right). We apply a Spearman’s rank correlation test and find that we can reject at 99.7% confidence the null hypothesis that there is no correlation between the O\vi column density for these systems and the number of kinematic components they exhibit.\(^{11} \) We emphasize that this is not a homogeneously selected sample, though we have tried to gather all reported systems that meet the selection criteria. Nevertheless, we find at least a strong suggestion that a large number of components lead to a strong O\vi absorber. This correlation could indicate that the O\vi is generally associated with the low-ionization material even if it does not reside in the same physical layers of the gas. This general behavior is expected in the interface scenario discussed above, though the problem of how just a few interfaces give \( \log N(\text{O} \, \text{vi}) > 14.5 \) remains.

The J1009+0713 system and other systems like it thus offer mild but not conclusive evidence in favor of the interface scenario. The broadening of strong O\vi into many detectable components and a correlation with a large number of velocity components in the H\,i and low ions are consistent with the basic expectations of the interface scenario. But the total quantity of O\vi substantially exceeds the expectations of the interface models, given the number of apparent cold gas clouds along the sightline. Three possible solutions to this puzzle are that a large number of cold clouds go undetected but their interfaces are seen, or the O\vi from a single interface is well above that calculated in models, or the interface model does not apply. It is still possible, perhaps even likely, that some fraction of the O\vi we observe is produced in interfaces, along with additional contributions from another mechanism. This system shows that further measurements of O\vi and Mg\,ii can provide more information about the correlation of hot gas with low-ionization gas for the same sample of absorbers. Such a study is planned as part of our larger survey.

\(^{11} \) The correlation is still strong if we assign only the four components detected at COS resolution to the J1009+0713 LLS; the data then reject the null hypothesis at 99.3% confidence.

### Table 3

| No. | Sightline | \( z_{\text{abs}} \) | \( \log N(\text{H}i) \) | \( \log N(\text{O} \, \text{vi}) \) | \( N_{\text{comp}} \) | Reference |
|-----|-----------|----------------|----------------|----------------|----------------|-----------|
| 1   | HE0153−4520 | 0.022601 | 16.61\(^{+0.12}_{-0.17}\) | 14.21 ± 0.01 | 1 | 1 |
| 2   | PKS0312−77  | 0.2026 | 18.22\(^{+0.15}_{-0.23}\) | 14.95 ± 0.05 | 6 | 2 |
| 3   | PKS0405−123 | 0.16692 | 16.45 ± 0.05 | 14.72 ± 0.02 | 5 | 3–7 |
| 4   | PG1116+215  | 0.13847 | 16.20 ± 0.04 | 13.68\(^{+0.10}_{-0.08}\) | 2 | 8 |
| 5   | PG1216+069  | 0.00632 | 19.32 ± 0.03 | <14.26 | 2 | 9 |
| 6   | "          | 0.12360 | >15.95 | 14.83 ± 0.10 | 9 | 10 |
| 7   | "          | 0.28189 | 16.70 ± 0.04 | 14.02 ± 0.02 | 3 | 10 |
| 8   | 3C 351.0    | 0.22111 | >17.0 | 14.27 ± 0.04 | 3 | 10 |
| 9   | PHL1811     | 0.07765 | 16.03 ± 0.07 | 13.56 ± 0.10 | 2 | 10 |
| 10  | "          | 0.08093 | 17.98 ± 0.05 | <13.59 | 2 | 11 |
| 11  | J1009+0713  | 0.3558 | 18.0–18.8 | 15.0 ± 0.2 | 9 | 12 |

**References.** (1) Savage et al. 2011; (2) Lehner et al. 2009; (3) Chen & Prochaska 2000; (4) Prochaska et al. 2004; (5) Williger et al. 2006; (6) Lehner et al. 2007; (7) Savage et al. 2010; (8) Sembach et al. 2004; (9) Tripp et al. 2005; (10) Tripp et al. 2008; (11) Jenkins et al. 2005; (12) This paper.
6. SUMMARY AND DISCUSSION

We have examined the ionization, metallicity, and association with galaxies of a newly discovered strong intervening O\textsc{iv} absorption-line system discovered in our COS data on J1009+0713. This system exhibits log N(O\textsc{iv}) = 15.0 spread kinematically over 400 km s\(^{-1}\). It appears to be associated with at least two galaxies at projected separations of 14 and 46 kpc from the sightline that have redshifts coincident with the detected gas. The system includes two similar LLS-strength components separated by 60–80 km s\(^{-1}\) with two weaker associated components 60–100 km s\(^{-1}\) away from these. The direct line measurements only constrain the gas metallicity in the two strongest components to Z = 0.1–1 Z\(_\odot\) owing to saturation of the H\textsc{i}. However, the detected ion ratios are well matched by a photoionization model in which simple clouds of total column density log N(H\textsc{i}) \(\simeq\) 20 and 5%–50% solar metallicity are ionized to a 1%–10% neutral fraction by a radiation field from star-forming regions at a distance of 20–100 kpc. In short, it appears that the bulk of this absorber traces gas that resides in the common halo environment of these galaxies and is ionized by their ongoing star formation. Similar modeling applied to the two outlying components, with log N(H\textsc{i}) = 14.8 and 16.5, are also consistent with their detected absorption models for log U \(\sim\) −2 and \(\sim\)25% solar metallicity. These outlying clouds also appear to be relatively highly ionized, with neutral fractions of 0.1%–1% even in the gas traced by low ions, but all with an additional, difficult-to-constrain, highly ionized component traced by O\textsc{iv}.

This system exhibits two galaxies ranging over two magnitudes in the rest-frame optical, the brightest (170_9) has one with \(M_\star = 6 \times 10^9 M\odot\) in stars.\(^\text{12}\) Galaxy 86_4 is 2 mag fainter with a total star formation rate of only about 1/10 that of 170_9. Based on emission-line measurements and its inferred stellar mass, the brighter galaxy 170_9 appears to be consistent with solar metallicity, while 86_4 is either consistent with solar metallicity or with \(\sim\)25% solar (depending on which branch of the R23 indicator is adopted). Since none of the detected gas components appear to require a solar metallicity (though B and C are consistent with solar if the photoionization modeling is discounted), we do not have positive evidence that any of the detected gas was brought into the sightline by outflows from the galaxies.

Several features of specific systems are worth comparing to the J1009+0713 LLS. The system at \(z = 0.167\) toward PKS0405−1219 (Chen & Prochaska 2000) lies \(\simeq 70\) kpc from two massive galaxies, is at least 0.1 solar and likely higher metallicity, and exhibits strong absorption from high ions up to N\textsc{v} and O\textsc{v} at log N(O\textsc{v}) = 14.6. The \(z = 0.0809\) LLS toward PHL 1811 (Jenkins et al. 2005) lies 34 and 87 kpc from two nearby L\textsc{v} galaxies, and has nearly a solar metallicity, but is not associated with highly ionized gas. Both of these absorbers show evidence of a predominantly ionized gas, though the PHL 1811 system also exhibits absorption by low ions. While our simple photoionization models shown above indicate a sub-solar metallicity for the J1009+0713 system, this model-dependent value may not reflect the true gas metallicity in the LLS components: the O\textsc{i} measurements are consistent with solar metallicity. The PKS0405−1219 system is a particularly interesting comparison to the J1009+0713 system, since the O\textsc{iv} in both cases is stronger and more kinematically complex than would be expected from the lower ionization species. While it is difficult to draw general conclusions from only three cases, it appears that galaxy halos may commonly host LLS absorption, that it can be quite enriched in metals to nearly solar abundances, and that it can be associated with large quantities of highly ionized gas. Based on the PKS0405−1219 and J1009+0713 systems, we speculate that LLS-strength absorption may be necessary to produce the strongest intervening O\textsc{iv} absorbers, log N(O\textsc{v}) \(\gtrsim\) 14.5. The general incidence of LLS in galaxy halos and its relationship to hot gas will be addressed by our larger survey, which should also be able to assess the gas metallicity in many cases. High metallicity in dense, cool gas located at >50 kpc from the nearest galaxies may indicate a major role for tidal stripping of dwarf satellites, or robust outflows from large galaxies or their dwarf satellites.

This sightline passes by a galaxy with nearly L\textsuperscript{*} and a dwarf galaxy possibly in its halo or interacting with it, which may have low metallicity. Their total velocity separation is only 25 km s\(^{-1}\), which suggests they are gravitationally associated. It is tempting to draw comparisons of this system to the Milky Way and its Magellanic Clouds. If the smaller galaxy has the metallicity of 25% indicated by their lower-branch R23 measurements, it could be associated with the A and/or D components in an outflow or tidal-stripping scenario. If so, some of the detected absorption components may arise in gas stripped from this dwarf galaxies, like the Magellanic Stream.

Alternatively, all the detected absorption components could have sub-solar metallicity and could trace low-metallicity, infalling material not unlike the large HVC complexes of the Milky Way. This inference and the high ionization state of the detected gas would imply that infalling, metal-poor gas enters halos and/or galaxies in ionized form, and is possibly associated with still more highly ionized material traced by O\textsc{v} that arises either in the hot diffuse galaxy halo itself or in interface zones of intermediate temperature between that hot ambient medium and the cooler infalling clouds. This scenario has been well developed for the Milky Way—further tests of its validity for external galaxies requires better knowledge of gas metallicities, kinematics in association to galaxies, and thus more well-studied cases.

In our combined COS and HIRES data we have used two important diagnostic lines for gas in galaxy halos—both O\textsc{iv} and Mg\textsc{ii}—that are typically not available in combination for the practical reason that they require both UV and optical data and galaxies at \(z \gtrsim 0.1\). Recently, Barton & Cooke (2009) and Chen et al. (2010) have systematically addressed the number density of Mg\textsc{ii} absorbers in the \(\sim 100\) kpc regions surrounding galaxies using absorption in QSO sightlines selected from SDSS. They find that the equivalent width of Mg\textsc{ii} increases at low impact parameter in a well-defined trend that has a detectable dependence on galaxy luminosity for those galaxies that exhibit Mg\textsc{ii} absorption. However, both Bowen & Chelouche (2011) and Gauthier et al. (2010) have found lower covering fractions of strong Mg\textsc{ii} surrounding more massive galaxies (LRGs) that indicate the cool gas covering fraction depends, perhaps strongly, on galaxy type and/or environment. For comparison with these samples, we obtained a total \(W_{1216} = 1250 \pm 15\) mÅ for the full LLS analyzed here, including 188 mÅ in component group A, 604 mÅ in component group B, and 472 mÅ in component group C. These findings are all within the range of the distributions found by these other studies. However, since we also detect H\textsc{i}, O\textsc{v}, and other multiphase UV ions in these

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\(^{12}\) The galaxy 92_7 appears in the SDSS photometric database with \(r = 22\), and appears distinctly in the WFC3 image, but we have not yet obtained its redshift. It may also be associated with this absorption-line system.
component groups, we can draw additional implications that are not possible based on Mg II alone.

First, we have used the detections of Mg II and the ionization stages of C, N, O, Mg, S, Si, and Fe to infer that the absorbing clouds have only a small portion, 1%–10% of their gas in the neutral phase. This finding implies that the gas mass traced by these absorbers could be significant. Indeed, Chen et al. (2010) inferred Mg II cloud masses of $\sim 2 \times 10^4 M_\odot$ and the total baryonic mass in halos of $3 \times 10^9 M_\odot$, using the important assumptions of 10% solar metallicity and a 10% ionization fraction for Mg II. These values are within the range permitted for the J1009+0713 clouds, where the ionization corrections and metallicities are better constrained by multiple ionization stages. Thus our findings indicate that the assumption of a significant mass correction to the observed Mg II is reasonable, and such absorbers could harbor significant mass. Moreover, the O VI suggests a possibly significant contribution of mass over and above that provided by Mg II systems. Finally, it may prove important to measure halo absorbers in both O VI and Mg II; components A, B, and C here hint that O VI and Mg II can have some relationship but may vary in their ratio by over an order of magnitude. Our larger survey was designed with the goal of detecting both lines in a significant sample of galaxies over a range of mass. We will thus be able to test the findings of Barton & Cooke (2009) and Chen et al. (2010) that Mg II correlates with galaxy luminosity, and also the finding by Bowen & Chelouche (2011) and Gauthier et al. (2010) that massive galaxies have less Mg II, while also exploring these relations in O VI for the same galaxies. These previous results, considered together with hints of a Mg II/O VI relationship for the J1009+0713 system, suggests this will be a fruitful line of research.

While it is among the strongest known O VI absorbers, this system at least superficially resembles the highly ionized, multiphase, O VI-bearing HVCs surrounding the Milky Way. For example, Fox et al. (2005) report conditions very similar to those we find here for two HVC complexes toward HE0226-4110 and PG0953+414 in the Milky Way halo. Specifically, their ionization modeling finds $\log U \sim -3.5$, subsonar metallicity, and $\log N_{HI} \sim -2$, but for clouds with $N(HI) \sim 16-16.5$. Like them, we have found consistent photoionization models for the present system that yet do not explain the observed abundance of O VI. Our findings also resonate with the recent survey of ionized silicon in the Milky Way HVC population by Shull et al. (2009) and Collins et al. (2009), who find typical values of $\log U \sim -3$ and 10%–30% solar metallicity or lower in these clouds with neutral fractions of $\leq 1%$. These favorable comparisons suggests that highly ionized, possibly metal-poor gas resides in the halos of star-forming galaxies as it does in the Milky Way—a key motivation for the survey that discovered this absorber. A more speculative but interesting inference can be drawn from the column density and ionization of the main components B and C. Were they exposed to a lower radiation field, because of a lower galactic $f_{esc}$ or SFR, they could instead appear as a sub-DLA or DLA with $N(HI) \sim 10^{20} \text{cm}^{-2}$ located at least 20 kpc from the nearest galaxy, and might have total column densities similar to the classical Milky Way HVC complexes. We note that recent surveys for 21 cm absorption affiliated with nearby galaxies (Borthakur et al. 2010; Gupta et al. 2010) have found 21 cm absorbers to be quite rare in galaxy halos. While this could be an indication that sub-DLAs and DLAs are rarely found at such large impact parameters (cf. Meiring et al. 2011b; Péroux et al. 2011), this remains an open question since 21 cm absorption depends on spin temperature, and sub-DLAs and DLAs might be missed in 21 cm absorption surveys if the gas is too warm. Our larger survey will address this problem by assessing the incidence of LLS, sub-DLAs, and DLAs in galaxy halos.

While the similarity of this absorber to some well-studied Milky Way HVCs provides an encouraging link between the HVCs and galaxy halo gas at large, this system also illustrates some important limitations that must be overcome to fully map out diffuse gas in halos. First, H I column densities in the range that gives an LLS but not a DLA, as here, are extremely difficult to constrain to a narrow range. This is especially true if the gas obviously occupies several clearly separated kinematic components that are blended in the Lyman series, as shown by our HIRES data. This unfortunate circumstance makes metallicities hard to estimate, even in cases where conditions are otherwise favorable for obtaining metal-line column densities, as they are here. While LLS are rare in the IGM at large, they may be quite common close to galaxies where total gas densities are high, even if the gas is typically highly ionized. This system also illustrates vividly that relating halo gas to its host galaxies is complicated by projection effects and by multiple galaxies lying along the sightline. We clearly cannot associate the absorption, especially in the O VI, with either of the two galaxy candidates in particular.

Finally, this system illustrates that detection of many ionization stages can constrain the physical parameters of the gas, but only for well-defined hypothetical physical scenarios, e.g., pure photoionization or pure collisional ionization. Combinations of such models, or non-standard scenarios such as interfaces and/or non-equilibrium calculations rapidly become too complex to test easily. Even for simple scenarios it is sometimes difficult to identify unique explanations for detected absorption. These considerations suggest that a large, systematic survey to assess possible variations could help by smoothing out variations along individual lines of sight. Our systematic survey of gas in galaxy halos, which serendipitously discovered this absorber, aims to establish a set of empirical facts about the content of gaseous halos. Yet multiphase, kinematically complex absorbers like this one pose a stiff challenge to our ability to build theoretical models that are up to the task of relating complex physical processes in galaxy halos to observable quantities. Progress in this area could significantly advance the cause of understanding galaxy formation at large.

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