QSO ABSORPTION SYSTEMS DETECTED IN Ne\textsc{viii}: HIGH-METALLICITY CLOUDS WITH A LARGE EFFECTIVE CROSS SECTION*

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ABSTRACT

Using high-resolution, high signal-to-noise ultraviolet spectra of the $z_{\text{em}} = 0.9754$ quasar PG1148+549 obtained with the Cosmic Origins Spectrograph (COS) on the Hubble Space Telescope, we study the physical conditions and abundances of Ne\textsc{viii}+O\textsc{vi} absorption line systems at $z_{\text{abs}} = 0.68381, 0.70152, 0.72478$. In addition to Ne\textsc{viii} and O\textsc{vi}, absorption lines from multiple ionization stages of oxygen (O\textsc{ii}, O\textsc{iii}, O\textsc{iv}) are detected and are well aligned with the more highly ionized species. We show that these absorbers are multiphase systems including hot gas ($T \approx 10^{7.5}$ K) that produces Ne\textsc{viii} and O\textsc{vi}, and the gas metallicity of the cool phase ranges from $Z = 0.3 Z_\odot$ to supersolar. The cool ($\approx 10^4$ K) phases have densities $n_H \approx 10^{-4}$ cm$^{-3}$ and small sizes (< 4 kpc); these cool clouds are likely to expand and dissipate, and the Ne\textsc{viii} may be within a transition layer between the cool gas and a surrounding, much hotter medium. The Ne\textsc{viii} redshift density, $dN/dz \approx 7^+3_-$, requires a large number of these clouds for every $L > 0.1 L^*$ galaxy and a large effective absorption cross section ($\gtrsim 100$ kpc), and indeed, we find a star-forming $\sim L^*$ galaxy at the redshift of $z_{\text{abs}} = 0.72478$ system, at an impact parameter of 217 kpc. Multiphase absorbers like these Ne\textsc{viii} systems are likely to be an important reservoir of baryons and metals in the circumgalactic media of galaxies.

Key words: galaxies: halos – intergalactic medium – quasars: absorption lines – quasars: individual (PG1148+549)

Online-only material: color figures

1. INTRODUCTION

The cosmic baryon fraction is now well constrained to a value $f_b = 0.17 \pm 0.01$ by both the interpretation of deuterium abundances in the framework of big bang nucleosynthesis (O’Meara et al. 2006; Pettini & Cooke 2012) and observations of the cosmic microwave background (Spergel et al. 2007). In contrast, the contributions of readily observed stellar and gas components in nearby galaxies are far below this value (Persic & Salucci 1992; Fukugita et al. 1998; Bell et al. 2003). One explanation for the “missing baryons” is that substantial quantities of low-density gas reside in the intergalactic medium (IGM) or in the halos of galaxies and groups (now generally referred to as the “circumgalactic” medium, CGM), and this matter is heated during infall into the dark matter potential wells that surround the visible galaxies (Davé et al. 2001; Cen & Wang 2006; Tepper-Garcia et al. 2011; Smith et al. 2011). This shock heating is a universal prediction of hydrodynamical simulations of structure formation, and it is expected to transform the gas from cool ($\approx 10^4$K) clouds that are straightforward to detect (Rauch et al. 1997; Weinberg et al. 1997) into hotter phases ($10^5$–10$^7$ K) that are much more difficult to study. How the intergalactic gas is physically processed as it descends into galaxies has important implications for galaxy evolution (Kereš et al. 2005, 2009; Dekel & Birnboim 2006; Bouché et al. 2010). For example, it is possible that some of the baryons cannot cool and fall into the star-forming disk (Maller & Bullock 2004) or are somehow prevented from entering galactic potential wells in the first place (Anderson & Bregman 2010). In any case, the observations indicate that the majority of the baryons in the universe are not located in the disks of galaxies; rather, they are sequestered in highly ionized, low-density gas in galaxy halos and the IGM. Currently, the most sensitive method to study such low-density plasmas is to search for the ultraviolet (UV) absorption lines imprinted on the spectrum of a background quasi-stellar object (QSO) from foreground, low-density material.

In addition to probing the missing baryons, QSO absorption spectroscopy of the CGM of galaxies provides unique insights on the roles played by gas inflows and outflows in galaxy evolution. Simple closed-box models of galactic chemical evolution fail to reproduce the distribution of stellar metallicities in the Milky Way and nearby galaxies (e.g., van den Bergh 1962; Larson 1972; Tinsley 1975; Pagel & Edmunds 1981; Tosi 1988; Worthey et al. 1996). This well-known “G-dwarf problem” indicates that galaxies continue to acquire gas from their intergalactic surroundings over much of their lifetimes. Exactly how this gas accretion occurs is an open question with important implications. In contrast to the traditional picture of hot accretion through a spherical accretion shock (e.g., White & Rees 1978), more recent theoretical studies suggest that gas accretes in filamentary structures, and it may be able to cool as it accretes so that it never approaches the virial temperature (Kereš et al. 2005, 2009; Dekel & Birnboim 2006; Brooks et al. 2009; Fumagalli et al. 2011; Stewart et al. 2011). Signatures of this “cold” accretion are difficult to identify, but recent QSO absorption-line studies have provided some observational evidence of cold accretion (Tripp et al. 2005; Ribaudo et al. 2011; Gaivalisco et al. 2011; Thom et al. 2011; Churchill et al. 2012; Kapeczak et al.

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These investigations have revealed very low metallicity gas in the halos of high-metallicity galaxies; this low-metallicity material is generally cool and could arise in the accretion flows, which are expected to be metal-poor.

Similarly, simulations and analytical models of galaxy formation and evolution require massive outflows to account for the observed properties of galaxies such as the ISM metallicities and the mass–metallicity relation, total stellar masses, discrepancies in the galaxy luminosity function compared to expectations from cold dark matter cosmology, and IGM enrichment (e.g., Dekel & Silk 1986; Springel & Hernquist 2003; Oppenheimer & Davé 2006). Feedback processes from current or recent star formation, either through radiatively driven or supernova-driven galactic-scale winds (or the combined effects of both processes, see Murray et al. 2011), are thought to play crucial roles in the evolution of a galaxy by injecting energy and mass into the CGM and beyond into the IGM. Such outflows are seen in nearby star-forming galaxies (Heckman et al. 1995; Martin et al. 2002; Veilleux et al. 2005) and are ubiquitous in some types of higher-redshift galaxies (Tremonti et al. 2007; Weiner et al. 2009; Steidel et al. 2010), but most of these studies provide little or no information on the full spatial extent, total mass, and overall impact of the outflows (cf. Tripp et al. 2011), either because the source of the outflow is used as the continuum source (and thus the spatial extent of the flow is unconstrained) or because the studies have inadequate leverage on the ionization and metallicity of the gas.

Which QSO absorption lines provide constraints on the missing baryons and inflows/outflows? The O\textsc{vi} λλ1031.9, 1037.6 lines arising from O^+\textsc{vii}, which has a peak ionization fraction at \(\sim 300,000 \text{ K}\) in collisional ionization equilibrium (CIE; Gnat & Sternberg 2007), have been used to trace hot gas in a range of environments from the local ISM to the CGM/IGM (e.g., Jenkins 1978; Tripp et al. 2000; Chen & Prochaska 2000; Howk et al. 2002; Sembach et al. 2003; Savage & Lehnert 2006; Stocke et al. 2006; Bowen et al. 2008; Wakker & Savage 2009; Chen & Mulchaey 2009; Howk et al. 2009; Lehnert et al. 2009; Tumlinson et al. 2011b; Narayanan et al. 2012, and references therein). Recent observations indicate that the extended halos of star-forming galaxies are filled with highly ionized and metal-enriched gas traced by O\textsc{vi}, and a large fraction of star-forming galaxies have detectable O\textsc{vi} absorption in their halos out to impact parameter \(\rho \approx 150 \text{ kpc}\) (Tumlinson et al. 2011a). Absorption by O\textsc{vi} is also detected in the halos of early-type galaxies, but less frequently (Tumlinson et al. 2011a), while strong H\textsc{i} absorption is ubiquitous in galaxy halos at \(\rho \leq 150 \text{ kpc}\) regardless of galaxy type (Thom et al. 2012). This circumgalactic material appears to contain a substantial amount of mass, comparable to the mass of the ISM in the galaxy itself (Tumlinson et al. 2011a; Tripp et al. 2011; Prochaska et al. 2011).

However, the physical nature of the O\textsc{vi}-bearing gas (e.g., collisionally ionized versus photoionized) is a debated and open question (Tripp et al. 2008), a question with important ramifications. Hydrodynamical simulations of galaxy evolution show that O\textsc{vi} absorbers typically reside in metal-enriched regions with overdensities \(\rho/\langle \rho \rangle \approx 1–100\) (Cen et al. 2001; Fang & Bryan 2001; Cen & Fang 2006; Davé et al. 2001; Tepper-Garcia et al. 2011; Oppenheimer & Davé 2009; Cen & Chisari 2011; Oppenheimer et al. 2012; Smith et al. 2011), and these models have made detailed predictions regarding the strength and physical nature of O\textsc{vi} absorbers as a function of impact parameter and galaxy luminosity (Ganguly et al. 2008; Stinson et al. 2012; Brady Ford et al. 2012). Simulations by Tepper-Garcia et al. (2011) and Cen & Chisari (2011) indicate that O\textsc{vi} does appear to trace primarily shock-heated gas, with the distribution of temperatures peaked at \(\sim 10^5\text{ K}\). However, \(\sim 30\%\) of the O\textsc{vi} systems in that simulation are at lower temperatures and are primarily photoionized by the UV background flux. Other simulations indicate that O\textsc{vi} and even Ne\textsc{viii} absorbers\(^6\) arise primarily in photoionized gas (Oppenheimer & Davé 2009; Oppenheimer et al. 2012). Interestingly, \(\sim 30\%\) of the observed O\textsc{vi} absorbers have characteristics of cool, photoionized gas (Tripp et al. 2008).

Despite recent advances in the UV absorption spectroscopy of the low-z IGM, several questions are still unanswered, due in part to the lack of adequate diagnostic lines at low redshift. The baryonic content, metallicity, and ionization mechanisms of the gas comprising the IGM and CGM are only loosely constrained, and the roles played by circumgalactic and intergalactic gases in galaxy evolution are still highly uncertain. Much of the work on low-z absorption lines has been accomplished with the Hubble Space Telescope (HST) Space Telescope Imaging Spectrograph (STIS) and Far Ultraviolet Spectroscopic Explorer (FUSE); these spectrographs can only study the brightest QSOs in reasonable exposure times. At the redshifts of the absorbers that have typically been studied with STIS and FUSE, only a limited set of absorption lines is available for analysis, and much of the determination of the physical conditions in the systems is based on H\textsc{i} and O\textsc{vi} alone, or on column density ratios of different ions such as C\textsc{iii}, Si\textsc{iii}, and O\textsc{vii}. Consequently, there can be degeneracies between effects due to ionization, non-solar relative abundances, and depletion by dust. Moreover, with a limited set of transitions, key species in the analysis (e.g., C\textsc{iii} and Si\textsc{iii}, which have only one strong resonance transition at \(\lambda > 912 \text{ Å}\)) are prone to saturation.

In order to overcome some of these issues and to better constrain the physical conditions in the IGM and CGM, we have undertaken a blind survey of \(z \sim 1\) QSOs with the Cosmic Origins Spectrograph (COS; Froning & Green 2009; Green et al. 2012). At moderate redshifts, we can access many of the numerous absorption lines in the far-UV (FUV) at \(\lambda_{\text{rest}} < 912 \text{ Å}\) (Verner et al. 1994), which provides several advantages compared to previous studies. First, multiple and adjacent ionization states of oxygen as well as many other ions (e.g., O\textsc{i}–O\textsc{vi}, N\textsc{i}–N\textsc{v}, S\textsc{ii}–S\textsc{v}, etc.) are available at \(\lambda \geq 600 \text{ Å}\) in the rest frame so that diagnostics of physical conditions ranging from \(T \approx 10^3 \text{ K}\) up to \(T \gg 10^5 \text{ K}\) can be exploited without confusion from assumptions about the relative abundances of the elements. Likewise, relative abundances can be constrained with the ambiguity from ionization corrections greatly reduced. Finally, in this wavelength range, many species have multiple transitions so that if a strong line is saturated or a line is badly affected by blending, other transitions can still be used to measure the column density of interest. At \(z \sim 0.5\), these transitions enter the bandpass of the COS on board the HST.

Aside from O\textsc{vi}, other highly ionized species have resonance transitions that are accessible in the FUV. For example, the Ne\textsc{vii} λλ770, 780 doublet enters the COS bandpass at \(z \gtrsim 0.45\). In diffuse halo gas or the IGM, it is difficult to photoionize neon
The ionization potential of Ne is 207 eV and the ionization potential of Ne is 239 eV. Neither stars nor background quasars produce an ionizing flux field with many photons at these energies (cf. Fox et al. 2005; Haardt & Madau 2012), and photoionization models typically require very low densities and, in turn, very large clouds to yield detectable quantities of Ne (Savage et al. 2005; Narayanan et al. 2011). While Ne is difficult to produce by photoionization, it can easily originate via collisional ionization in gas that is sufficiently hot. Consequently, Ne is expected to be an unambiguous indicator of collisionally ionized hot gas. Several intervening absorption systems bearing Ne have been discovered, indicating highly ionized and multiphase gas with temperatures of $T = 10^5–10^6$ K in the hot material (Savage et al. 2005; Tripp et al. 2011; Narayanan et al. 2011, 2012).

The excellent sensitivity of COS in the UV provides an opportunity to study the IGM and CGM in much more detail than has been achievable in the past. Using our high signal-to-noise ratio (S/N) COS spectrum of the QSO PG1148+549, in this paper we study in detail absorption systems at $z \approx 0.7$ where we have access to a number of ionization states of oxygen (O vi to O vi) and the Ne vii λ770, 780 doublet; we also place limits on other banks of (undetected) adjacent ions such as the sulfur ions. We will show that the O vi and Ne vii do indeed arise in plasma with $T \gg 10^5$ K, but this hot gas has an intimate relationship with lower ionization material—the hot gas likely originates in some sort of interface on the surface of the cooler, low-ionization clouds (e.g., Kwak et al. 2011). We will also show that these Ne vii systems are remarkably metal-rich, and when information on nearby galaxies is available, the Ne vii systems tend to be surprisingly far from luminous galaxies. The organization of the paper is as follows. In Section 2, we discuss the COS observations and data handling, details of the analysis of each absorption system are given in Section 3. Section 4 describes the ionization modeling, results are given in Section 5, a discussion of the galaxies in the field are given in Section 6, and Section 7 gives a summary and discussion. Throughout this paper we assume the 737 cosmology: $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

2. OBSERVATIONS

The observations of PG1148+549 presented here were taken as part of HST program 11741 (PI: Tripp), a blind survey for highly ionized species such as O vi, Ne viii, and Mg x, as well as lower ionization stages that constrain the physical conditions and metallicity of the multiphase galactic halos, in the spectra of $z \sim 1–1.5$ UV-bright quasars. Targets for this sample were selected only based on their redshift ($z \gtrsim 0.9$) and flux in the FUV. No consideration was given to previously known information about absorption systems when selecting targets for this program, with two exceptions: (1) if a target was known to have a broad absorption line system in its spectrum, it was excluded because such systems, which are known to be ejected gas located very close to the QSO nucleus, have complex and temporally variable absorption profiles that spread over large wavelength ranges (see, e.g., Trump et al. 2006) and seriously compromise our ability to study intervening gaseous halos and intergalactic gas clouds. (2) If a target was known to have a strong Lyman limit absorber that completely suppresses the flux shortward of its redshifted Lyman limit in some portion of the COS FUV band, the target was excluded in order to maximize the wavelength range that can be usefully searched for the species of interest.8 While PG1148+549 had been previously observed with the HST Faint Object Spectrograph (FOS, $R \sim 1300$) in programs 4952 and 6210 (Hamann et al. 1998; Bechtold et al. 2002), the resolution and sensitivity of the FOS spectra are far too low for the purposes of this work, which requires detection of $\sim$20 mA lines and precise and reliable measurement of line centroids, line widths, and profile kinematics/component structure.

As summarized in Table 1, the COS spectra of PG1148+549 were acquired on 2009 December 25–30. To cover the full FUV wavelength range of COS from 1150 to 1800 Å, observations were obtained with both the G130M and G160M gratings, and for each grating two central wavelength tilts were used to fill in the gap between the two COS detector segments. In addition, several exposures with multiple focal-plane positions (FP-splits) were obtained with each central-wavelength setting so that the effects of fixed-pattern noise are mitigated when the individual exposures are aligned and combined. Overall, the total exposure times were estimated based on the goal of detecting Ne vii lines as weak as those reported by Savage et al. (2005), i.e., exposure times were calculated to achieve adequate S/N to detect lines with equivalent widths of 20–30 mA with good statistical significance over the full wavelength region where the doublet is redshifted into the HST bandpass.

The COS data were processed in the same manner as described in Meiring et al. (2011). The COS FUV detector backgrounds are very low (Green et al. 2012), so in the cores of strong absorption lines, the total counts can be low enough so that Poissonian statistics should be used to estimate the flux uncertainties. Since COS has photon-counting detectors, we used the counts in each pixel to determine flux uncertainties, using Poissonian statistics in regions of low counts. In addition to multiple FP-split exposures, flat fielding was applied to further reduce residual fixed-pattern noise, primarily from

7 The Ne vii doublet has also been detected in a number of “proximate” absorbers with $z_{\text{abs}} \approx z_{\text{QSO}}$ (e.g., Petitjean & Srianand 1999; Ganguly et al. 2006; Muzahid et al. 2012, 2013); these proximate absorbers show evidence that they are close to the central engine of the QSO and thus probe a different aspect of galaxies than the intervening systems. In this paper, we are primarily interested in diffuse gas in the halos of galaxies and the IGM, so we do not include the proximate systems in our discussions.

8 Note that a target was not rejected if its spectrum showed a partial Lyman limit, i.e., only a fully black Lyman limit absorption led to rejection.
the COS gridwires. Strong and narrow absorption lines were used to cross-correlate and align the individual exposures, and the reduced and coadded spectra were binned by 3 pixels since the standard pipeline COS data are oversampled with a \( \sim 6 \) pixel wide resolution element (i.e., the data were binned to Nyquist sampling of \( \sim 2 \) pixels per resolution element). All measurements and analyses in this paper were performed on the binned spectra. The binned spectra have a resolution of \( 15-20 \) km s\(^{-1}\) per resolution element, and the S/N of the final, fully combined COS spectrum ranges from 20 to 40 per resolution element, with S/N \( > 29 \) in most continuum pixels between 1180 and 1550 Å.

In principle, there are several potential sources of noise in addition to photon-counting statistics such as uncertainties in the continuum placement, uncertainties in the flux zero point, and fixed-pattern noise. Due to the low detector backgrounds of COS, uncertainties in the flux zero point are very small and can be safely neglected. We also expect the fixed-pattern noise contribution to be small due to our use of FP splits and flat fielding. To check this, we have measured the rms noise in line-free continuum regions across the full wavelength range of the spectrum, and we find that the noise in the continuum is in good agreement with the expected noise based on photon-counting statistics, which indicates that fixed-pattern noise makes a small and generally unimportant contribution to the overall measurement uncertainties. However, in some regions, continuum-placement uncertainty can be comparable to the statistical noise, so we have included this term in our error analyses.

While the COS FUV absorption lines are the central data of this survey, we also obtained several ancillary observations from the ground to support the COS analyses.

First, to search for Mg \( \alpha \lambda \lambda 2796, 2803 \) absorption affiliated with systems of interest, we obtained high-resolution optical spectra of PG1148+549 with the High Resolution Echelle Spectrograph (HIRES) at the Keck Observatory. Two 900-second exposures were recorded with HIRESb on 2012 April 13 covering the 3300–5880 Å range with a spectral resolution of 6 km s\(^{-1}\) (FWHM). In the wavelength range relevant to the absorption systems studied in this paper, the HIRES data have S/N = 40 to 50 per resolution element at the expected wavelengths of the Mg \( \alpha \) doublet.

Second, we obtained deep multiband imaging of the PG1148+549 field with the twin Large Binocular Cameras (LBCs) on the 2 × 8.4 m Large Binocular Telescope (LBT). The LBCs, fully described in Giallongo et al. (2008), provide simultaneous imaging in two bands over a \( \sim 23' \) field of view centered on the QSO. We obtained imaging in the \( UBV \) bands, dithering between exposures to fill in the inter-chip gaps between the four CCDs. The total \( U \) and \( I \) band exposures total 2500 s, while the \( B \) and \( V \) band exposures total 350 s. The imaging was taken through very light cirrus with times ranging from 600 to 800 s, on 2010 April 5. The LRIS spectra verified that two of the targets are stars, but the other two objects are galaxies, including a galaxy at the redshift of one of the Ne \( \pii \) absorbers.

3. ABSORPTION-LINE MEASUREMENTS

After normalizing the continuum in regions of interest by interactively fitting cubic splines to the data, we employed two techniques for absorption-line measurements. First, we used the apparent column density method (Savage & Sembach 1991; Jenkins 1996) in which the apparent optical depth in a pixel, \( \tau_a(v) = \ln[I_a/\bar{I}(v)] \), where \( I_a(v) \) is the observed flux and \( \bar{I}(v) \) is the continuum flux at velocity \( v \), is used to estimate the column density in that pixel, \( N_a(v) = (m_e/e^2)\tau_a(v)/(f\lambda) \), where \( f \) is the oscillator strength and \( \lambda \) is the wavelength of the transition, and the other symbols have their usual meanings. Apparent column density profiles are useful in a variety of ways: (1) the profiles provide an efficient means to confirm line identifications, (2) \( N_a(v) \) profiles can be scaled and overplotted to visually compare the kinematics and component structure of various species, and (3) the apparent column density profiles provide a quick assessment of whether lines are affected by saturation (through comparison of weak versus strong transition of a specific species). If a profile is not affected by saturation, it can be integrated to obtain the total column density, \( N(\text{total}) = \int N_a(v) \, dv \).

Second, we used Voigt profile fitting to determine the column densities, velocity centroids, and \( b \)-values of H\( \alpha \) and metal absorption lines detected in the PG1148+549 spectrum. To account for the broad wings in the COS line-spread function (LSF; Ghavamian et al. 2009; Green et al. 2012), the synthetic Voigt profiles were convolved with the COS LSF at the nearest tabulated wavelength (Ghavamian et al. 2009). Whenever possible, multiple transitions were fit simultaneously (e.g., Ly\( \beta \), \( \gamma \), \( \delta \)) to determine the best-fitting column densities.

This paper is focused on Ne \( \piii/O \pii \) absorption systems, but since previous studies have always found that these systems also exhibit absorption from lower ionization stages, we have searched for absorption lines from the strongest species expected in warm ionized gas as well. In the COS data, we search for ions of carbon, nitrogen, oxygen, and sulfur, and we use the Keck spectra to place upper limits on Mg \( \pii \). Upper limits on column densities for non-detected species were derived by determining a 3\( \sigma \) upper limit on the rest-frame equivalent width of the undetected ion, including an allowance for continuum placement uncertainty using the method of Sembach & Savage (1992), and then the equivalent width upper limit was converted to a column density upper limit assuming the linear curve of growth applies. Often the COS data cover multiple transitions of a given ion; our strategy for placing upper limits is to use the strongest transition (and thereby obtain the tightest constraint) that is not badly affected by blending with unrelated lines.

The COS wavelength solution is known to have inaccuracies at the level of one to two (binned) pixels, and these inaccuracies are particularly noticeable in regions of the spectra that are recorded near the edges of the detector segments (Savage et al. 2011b); the worst errors can approach 30 km s\(^{-1}\), although typically the errors are smaller than this. In some cases, we are able to correct for this wavelength calibration problem by comparing lines that should be well aligned (e.g., H\( \alpha \) Lyman
series lines or different transitions of the same metal ion), and we have applied shifts in velocity to improve the wavelength calibration when such comparisons have been possible. We define the systemic redshifts of the absorbers to be the centroid of the strongest component of the \( \text{O} \, \text{vi} \) profiles.

4. \( \text{Ne} \, \text{viii} \) ABSORPTION SYSTEMS

Using the line-identification procedure of Tripp et al. (2008), we have identified three \( \text{Ne} \, \text{viii} \) absorption systems in the spectrum of PG1148+549 at \( z = 0.68381, 0.70152, 0.72478 \). In addition to \( \text{Ne} \, \text{viii} \), we detect multiple ionization stages of oxygen, nitrogen, and carbon in these absorption systems, and we are able to place strong constraints on the \( \text{H} \, \text{i} \) content of the absorption systems, at least for the cooler phases. In this section we present basic information and measurements for these \( \text{Ne} \, \text{viii} \) systems.

4.1. The \( z_{\text{abs}} = 0.68381 \) System

The \( \text{Ne} \, \text{viii} \) absorber with the highest affiliated \( \text{H} \, \text{i} \) column density (and the largest number of affiliated metals) is the system at \( z_{\text{abs}} = 0.68381 \). In this absorber we detect lines of \( \text{H} \, \text{i} \), \( \text{C} \, \text{iii} \), \( \text{O} \, \text{iii} \), \( \text{N} \, \text{iv} \), \( \text{O} \, \text{iv} \), \( \text{O} \, \text{vi} \), and \( \text{Ne} \, \text{viii} \). We also find a marginal feature at the expected wavelength of the strongest \( \text{O} \, \text{ii} \) line at 834.47 Å; however, the significance of this feature is <3\( \sigma \), so we can only place an upper limit on \( N(\text{O} \, \text{ii}) \). Likewise, no statistically significant \( \text{N} \, \text{iii} \) lines are evident. Velocity plots for \( \text{H} \, \text{i} \) and metal-line absorption profiles for this system are shown in Figure 1; in this figure and in all velocity plots in this paper, the velocity scale is in the rest frame of the absorber, and we define the systemic redshifts of the absorbers to be the centroid of the strongest component of the \( \text{O} \, \text{vi} \) profiles. Note that in this figure (and the analogous figures for the other absorbers), we show some lines to alert the reader to problematic blends with lines from other redshifts, which are marked with magenta dots. In Figure 1, the best-fit Voigt profiles are overlaid in red. We have used two components to fit the absorption lines in this system. At this redshift, the \( \text{H} \, \text{i} \) \( \text{Ly}\alpha \) line is redshifted beyond the long-wavelength end of the COS spectrum. However, we detect \( \text{H} \, \text{i} \) transitions from \( \text{Ly}\beta \) up to \( \text{Ly}\epsilon \) (\( \lambda 937.80 \)) in the COS FUV spectrum (see Figure 1). Rest-frame equivalent widths and integrated apparent column densities of the \( \text{H} \, \text{i} \) and metal...
Table 2
Equivalent Widths and Integrated Apparent Column Densities for Transitions Observed in the $z_{abs} = 0.68381$ System\textsuperscript{a}

| Transition | $W_r$ (mÅ) | log [$N_v$ (cm$^{-2}$)] |
|------------|-----------|----------------------|
| H$\alpha$ 1025.72 \ldots | 276 ± 17 | 14.77 ± 0.02 |
| H$\beta$ 1049.74 \ldots | 54 ± 15 | 14.74 ± 0.11 |
| H$\gamma$ 1087.80 | 37 ± 9 | 14.82 ± 0.09 |
| C$\alpha$ 5696.2 | $<19^b$ | $<13.2^d$ |
| O$\beta$ 3727.64 | $<24^c$ | $<13.5^d$ |
| Mg$\alpha$ 2796.35 | $<20^c$ | $<11.7^d$ |
| N$\gamma$ 6557.85 | $<34^c$ | $<13.5^d$ |
| S$\alpha$ 6302.55 | 188 ± 12 | 13.65 ± 0.02 |
| S$\beta$ 6363.82 | $<15^c$ | $<12.7^d$ |
| O$\delta$ 6300.15 \ldots | 80 ± 8 | 13.47 ± 0.04 |
| O$\gamma$ 6301.87 \ldots | 153 ± 8 | 14.60 ± 0.02 |
| S$\delta$ 6380.04 \ldots | $<15^c$ | $<13.4^d$ |
| O$\gamma$ 1031.93 \ldots | 234 ± 19 | 14.47 ± 0.03 |
| O$\delta$ 1037.62 \ldots | 149 ± 23 | 14.50 ± 0.06 |
| S$\gamma$ 1084.52 \ldots | $<35^c$ | $<13.3^d$ |
| Ne VIII 3774.41 | 51 ± 12 | 13.98 ± 0.09 |

Notes.

\textsuperscript{a} The O$\delta$ 1072.33 and $\lambda$ 832.93 lines are detected but are not listed in this table because both of these transitions are significantly blended with unrelated absorption features (see Figure 1), and thus the integrated quantities are not very useful. We estimate the O$\delta$ column densities by jointly fitting Voigt profiles to both O$$\delta$$ lines as well as the blended lines.

\textsuperscript{b} We use the C$\alpha$ 2300 instead of the stronger C$\alpha$ 903.96 transition because the 903.96 Å line is blended into the wing of a strong Ly$\alpha$ line at $z_{abs} = 0.2525$.  

\textsuperscript{c} $3\sigma$ upper limit obtained by integration over $-75 < v < 100$ km s$^{-1}$.

\textsuperscript{d} Upper limit based on the $3\sigma$ upper limit on $W_r$, assuming the line is in the linear regime of the curve of growth.

\textsuperscript{e} Derived from the Keck/HIRES data.

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Figure 2. Apparent column density profiles (Section 3) of the O vi and O vii lines from the $z_{abs} = 0.68381$ system. The O vi 787 line has been scaled by a factor of 0.75 for illustration. As in Figure 1 and all velocity plots in this paper, the velocity scale is in the rest frame of the absorption system. The $y$ axis is plotted in units of $10^{12}$ particles cm$^{-2}$ (km s$^{-1}$)$^{-1}$.

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

Figure 3. Apparent column density profiles of the O vi and Ne viii lines from $z_{abs} = 0.68381$ system. The O vi $\lambda$1031 line has been scaled by a factor of 0.4 for illustration.

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

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lines in this system are given in Table 2, and column densities determined by Voigt profile fitting are listed in Table 3.

To support our line identifications, we compare the apparent column density profiles of the O vii $\lambda$787.71, O vi $\lambda$1031.93, 1037.62, and Ne viii $\lambda$770.41, 780.32 lines in Figures 2 and 3. While there are multiple resonance transitions of O iv in the FUV (Verner et al. 1994), at $z_{abs} = 0.68381$, only the O iv $\lambda$787.71 line is redshifted into the wavelength range of our COS spectrum. Therefore, one might question the reliability of the O iv identification. However, as we can see from Figures 1 and 2, the profile of the O iv $\lambda$787.71 line matches the profiles of the O vii doublet over a large span of pixels, and this indicates that the O iv identification is secure.

Similarly, the $N_v(v)$ plots are helpful for the Ne viii identification. The Ne viii $\lambda$780.32 line is certainly blended with
O  iii λ832.93 at $z_{abs} = 0.57757$, and this Ne vii transition could also be blended with C  iii λ977.02 at $z_{abs} \approx 0.3448$. The O  iii transition is clearly identified; the $z_{abs} = 0.57757$ absorber shows many H  i Lyman series lines and metals with a distinctive two-component structure that matches the O  iii profile. One of the O  iii components at $z_{abs} = 0.57757$ is redshifted of the expected wavelength of Ne vii 780.32 line, but the other O  iii component falls near the center of the expected Ne vii feature. The contribution of C  iii λ977.02 at $z_{abs} \approx 0.3448$ to this blend is less certain; a well-detected Lyα line is found at $z_{abs} = 0.3448$, and while this Lyα absorber has very few affiliated metals, C  iii λ977.02 is one of the strongest UV lines, and there could be some optical depth from C  iii in the blend as well. Given these blends, it is not surprising that the Ne vii 780.32 profile appears to be stronger than the Ne viii 770.41 line (see Figure 3) because some of the optical depth in the Ne vii 780.32 profile is due to other species at other redshifts. Unfortunately, only one O  iii line from $z_{abs} = 0.57757$ is redshifted into the COS spectrum, so we cannot remove the O  iii optical depth from the blend by modeling. Therefore, we must rely on the (unblended) Ne viii 770.41 transition alone in $z_{abs} = 0.68381$ absorber. We can find no other plausible metal-line identifications for the Ne vii 770.41 candidate, and the fact that the shape of the Ne vii 770.41 profile matches the shape of the well-detected O vi lines at this redshift (see Figures 1 and 3) supports the identification of the feature as Ne viii.

Finally, we note that the O  iii λ832.93 line at $z_{abs} = 0.68381$ is blended with the Milky Way Si iv λ1402.77 transition. In this case, we can correct for the blend by modeling; by fitting the corresponding Milky Way Si iv λ1393 line, we can predict

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**Table 4**

| Transition | $W_r$ (mÅ) | $\log [N_v]$ (cm$^{-2}$) |
|------------|-------------|--------------------------|
| H  i λ1025.72... | <36$^b$ | <13.7$^b$ |
| C  iii λ903.96... | <18$^b$ | <12.5$^b$ |
| N  ii λ1915.61... | <31$^b$ | <13.4$^b$ |
| O  iii λ834.47... | <20$^b$ | <13.4$^b$ |
| Mg  ii λ2796.35... | <17$^b,d$ | <11.6$^d$ |
| C  iii λ977.02... | 126 ± 16 | 13.41 ± 0.05 |
| Ne  iii λ868.51... | <26$^b$ | <13.4$^b$ |
| O  iii λ832.93... | 18 ± 5 | 13.48 ± 0.09 |
| S  iii λ698.73... | <13$^b$ | <12.6$^b$ |
| O vi λ787.71... | 75 ± 9 | 14.18 ± 0.04 |
| S iv λ809.67... | <19$^b$ | <13.5$^b$ |
| S v λ786.48... | <20$^b$ | <12.4$^b$ |
| O vii λ1031.93... | 168 ± 19 | 14.29 ± 0.04 |
| Ne vii λ1037.62... | 113 ± 19 | 14.35 ± 0.06 |
| S vii λ933.38... | <30$^b$ | <12.9$^b$ |
| Ne viii λ770.41... | 28 ± 5 | 13.75 ± 0.07 |
| Ne viii λ780.32... | 18 ± 6 | 13.86 ± 0.11 |

**Notes.**

$^a$ Quantities in this table do not include the weak component at $v = -125$ km s$^{-1}$, which is only marginally detected in O vi and is not detected in Ne viii.

$^b$ 3σ upper limit obtained by integration over $-50 < v < 100$ km s$^{-1}$.

$^c$ Upper limit based on the 3σ upper limit on $W_r$, assuming the line is in the linear regime of the curve of growth.

$^d$ Derived from the Keck/HIRES data.

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4.2. The $z_{abs} = 0.70152$ System

A variety of absorption lines from metals are evident at $z_{abs} = 0.70152$, including C  iii, O  iii, O iv, Ne vii, and O vi. We do not detect N  iii or N  iv, but the only N  iv transition that is redshifted into the COS spectrum is lost in a blend with the strong Galactic O 1λ1302.17 absorption line. The N  iii λ989.80 line is blended with a Lyα line at $z_{abs} = 0.3862$, but the N  iii λ685.51 transition, which is nearly twice stronger, is not observed either. As in the $z_{abs} = 0.68381$ system, the H  i Lyα line is redshifted out of the COS spectrum, but unlike the $z_{abs} = 0.68381$ absorber, no higher Lyman series lines are detected in the $z_{abs} = 0.70152$ system. Velocity plots of the absorption lines from this system, including the undetected Lyβ line, are shown in Figure 4, with the best-fit profiles overlaid in red. Equivalent widths and column densities for the $z_{abs} = 0.70152$ absorber, measured with the apparent column density technique and profile fitting, can be found in Tables 4 and 5. Two well-detected components at $v = 0$ and 59 km s$^{-1}$ are readily apparent in the absorption profiles of C  iii, O iv, and O vi, but Ne vii is clearly detected only in the $v = 0$ km s$^{-1}$ feature. A third component is clearly seen at $v = -125$ km s$^{-1}$ in the C  iii and O iv transitions, and weak but consistent features are present at this velocity in O  iii and O vi. The O vi at this velocity is particularly marginal; the
Figure 4. Continuum-normalized absorption profiles of the $z_{\text{abs}} = 0.70152$ absorption system plotted in the rest frame of the absorber, as in Figure 1. (A color version of this figure is available in the online journal.)

Figure 5. Apparent column density profiles of the O iv and O vi lines from the $z_{\text{abs}} = 0.70152$ system. The O iv $\lambda 787.71$ line has been scaled by a factor of 1.5 for illustration. (A color version of this figure is available in the online journal.)
The absence of Lyβ absorption is an interesting feature of this absorber—combined with detection of strong metal lines, this suggests that this is a highly metal-enriched system, as we will discuss further in Section 5. Integrating over the full velocity range of the detected metal absorption (−50 < v < 100 km s$^{-1}$), we obtain log N(H i) < 13.7 (3σ). However, we noted above that two components are evident in this system, and will consider the implied metallicities of this absorber on a component-by-component basis in the following section, so have also obtained limits on N(H i) in each of the components. For the feature at v = 0 km s$^{-1}$, we integrate from −50 to 50 km s$^{-1}$ and obtain log N(H i) < 13.6 (3σ). For the v = 60 km s$^{-1}$ component, we integrate from 50 to 100 km s$^{-1}$ and obtain log N(H i) < 13.4 (3σ).

4.3. The z$_{abs}$ = 0.72478 System

The final Ne viii absorber is similar to the system at z$_{abs}$ = 0.70152 with detections of O iv, O vi, and Ne viii and no affiliated H i absorption in Lyβ or higher Lyman series lines. We show a velocity stack plot of selected lines in Figure 7, and we compare the N$_{abs}(v)$ profiles of O iv, O vi, and Ne viii in Figures 8 and 9. The data indicate only a single component in this absorber. No H i absorption is detected, and we derive an upper limit of log N(H i) < 13.7 by integrating the Lyβ $\lambda$1025 line region from −75 to +75 km s$^{-1}$. Equivalent widths and column densities for this system are summarized in Tables 6 and 7. The O iv $\lambda$787.71 and O vi $\lambda\lambda$1031.93, 1037.62 lines are detected in this system at high significance, and the good correspondence of the Ne viii profiles with the other lines supports the Ne viii identification.

5. IONIZATION MODELING

We now turn to analysis of the physical conditions and metallicity of the Ne viii/O vi absorbers. Given the velocity alignment of the Ne viii and O vi absorptions, it is clear that there is some sort of relationship between the Ne viii-bearing gas and the lower ionization material. The velocity alignment does not necessarily indicate that the Ne viii arises in a single-phase cloud that is coeval with the lower ions; it is possible that this indicates that the Ne viii originates in an interface on the surface of a lower ionization cloud, for example. To investigate this relationship and probe the nature of the Ne viii absorbers, we holistically analyze the ionization mechanism(s) for all detected ionization stages, not just the Ne viii. For this purpose, we follow the methodology of Tripp et al. (2011), which is brieMLy summarized as follows. We first constrain the portion of the absorbing gas that can be attributed to the ionized hot phase (Section 5.2). For this purpose, we follow the methodology of Tripp et al. (2011), which is briefly summarized as follows. We first constrain the portion of the absorbing gas that can be attributed to the ionized hot phase (Section 5.2).
5.1. Photoionization

We model photoionized gas using cloudy version 8.00 (Ferland et al. 1998). We have used the Haardt & Madau extragalactic background spectrum (Haardt & Madau 1996) at $z = 0.7$, with the modifications and updates described in Haardt & Madau (2001), including contributions from both active galactic nuclei (AGNs) and galaxies. We treat the absorbers as plane-parallel slabs with constant density, and we initially assume that the elements have the same relative abundances observed in the Sun (Lodders 2003; Asplund et al. 2009); after running the initial models, we consider whether there is evidence for departures from the solar abundance patterns. Local flux sources (starlight from galaxies) can be brighter than the diffuse UV background if the escape fraction of the ionizing flux is sufficiently high (Fox et al. 2005; Misawa et al. 2009). However, observational studies have not yet provided strong evidence for a high escape fraction, so we will mainly employ the Haardt & Madau (1996) flux as our fiducial model in this paper.

5.1.1. $z_{\text{abs}} = 0.68381$

Figure 10 shows our photoionization model for the component at $v = 0$ km s$^{-1}$ of the absorption system at $z_{\text{abs}} = 0.68381$. In this figure, the column densities predicted by the cloudy model are plotted with smooth curves, and the observed column densities and upper limits are displayed with large, discrete symbols at the value of $U$ that matches the observed O$\text{iv}/$O$\text{iii}$ ratio (in some cases, small offsets have been applied for clarity because the symbols overlap). The legends in each panel label the curves and symbols. This model matches the observed O$\text{iv}/$O$\text{iii}$ ratio with log $U = -1.60$ and metallicity$^{10} \text{[X/H]} = -0.5$. Various parameters of this photoionization model are summarized in Table 8.

With the ionization parameter constrained by O$\text{iv}/$O$\text{iii}$, several interesting implications unfold. First and foremost, this photoionization model falls woefully short of the observed column densities of O$\text{vi}$ and Ne$\text{viii}$: the observed $N$(O$\text{vi}$) is 25 times higher than the model prediction, and the observed $N$(Ne$\text{viii}$) is many orders of magnitude higher than the model, which predicts negligible amounts of Ne$\text{viii}$ in the photoionized gas at log $U = -1.6$. The high-ion absorption must arise in a separate phase. Second, the model is roughly consistent with the measurements for intermediate-ionization stages of carbon, nitrogen, and sulfur (lower panels). However, the model seems to require modest underabundances of carbon and nitrogen;

$^{10}$ We use the usual notation where $Z$ is the absolute metallicity and the logarithmic metallicity $\text{[X/H]} = \log \left[ N(X) / N(H) \right] - \log (X/H)_{\odot}$.
the observed columns of both C III and N IV are somewhat lower than predicted by the model, and the upper limit on N III is also in tension with the model, which indicates that N III should be marginally detected.\textsuperscript{11} To fit the C III and N IV, this model requires modest relative abundance adjustments; relative to oxygen, the model requires [C/O] = −0.4 and [N/O] = −0.2. The upper limits on the sulfur ions are consistent with the model but do not provide additional information. The sulfur ion column densities are all expected to be below the detection threshold (lowest panel in Figure 10). However, the predicted sulfur columns are only moderately below the observed upper limits, so higher S/N observations could provide information on the relative abundances of sulfur as well. Even though the Mg II λλ 2796.35, 2803.53 doublet is extremely strong and places tight upper limits on N(Mg II), we see from Figure 10 that Mg II is easily photoionized in these conditions and is expected to be undetectable. Indeed, the photoionization model indicates that all of the low ions that we can constrain (e.g., C II, N II, O II, Mg II) should have very low column densities that are well below the observed upper limits. As we discuss below, underabundances of C and N are not necessarily surprising.

We note that the discrepancies between the model and the observed O VI and Ne VIII columns, as well as the underabundances implied by C III and N IV, cannot be attributed to measurement uncertainties; the column density uncertainties are generally

\textsuperscript{11} We note that a weak feature is apparent at the expected wavelength of N III λ 685.51, but the feature is not recorded at adequate significance to provide a reliable measurement.

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**Figure 8.** Apparent column density profiles of the O IV and O VI lines of the z\textsubscript{abs} = 0.72478 system. The O IV λ 787.71 line has been scaled by a factor of 1.5 for purposes of comparison. (A color version of this figure is available in the online journal.)

**Figure 9.** Apparent column density profiles of the O VI and Ne VIII lines from the z\textsubscript{abs} = 0.72478 system. The O VI λ 1031.93 line has been scaled by a factor of 0.75 for comparison with the other lines. (A color version of this figure is available in the online journal.)

**Figure 10.** Photoionization modeling of the v = 0 km s\textsuperscript{-1} component in the multiphase O VI/Ne VIII absorber at z\textsubscript{abs} = 0.68381, assuming the gas is photoionized by the diffuse UV background from quasars and galaxies as calculated by Haardt & Madau (2001). In each panel, the column densities predicted by the photoionization model, as a function of ionization parameter U, are shown with smooth curves. The observed column densities and 3\textsigma upper limits are indicated with large symbols at log U ≈ −1.6. Generally, the uncertainties in the observed column densities are comparable to the symbol sizes (see Tables 2–7). The species corresponding to each curve and symbol are indicated by the legend in the upper-left corner of each panel. In this figure, the overall metallicity is Z = 0.3 Z\textsubscript{⊙}. (A color version of this figure is available in the online journal.)
smaller than the symbol sizes in Figure 10. A potential source of systematic uncertainty in this analysis is the assumed ionizing flux field. The shape and intensity of the UV background are constrained by models (e.g., Haardt & Madau 1996) but are only loosely constrained by observations (Davé & Tripp 2001, and references therein). In principle, with fine tuning, modifications of the shape of the radiation field could alleviate the C iii and N iv discrepancies, but usually this is not helpful because the ionization potentials of O iii/O iv, C iii/C iv, and N iii/N iv are too similar. The observations may be indicating real underabundances of C and N.

On the other hand, it is interesting to consider whether adjustments of the ionizing flux field could lead to higher O vi and Ne vii columns and thereby alleviate this problem. For example, it is known that obscured AGNs comprise an important portion of the X-ray background (e.g., Mushotzky et al. 2000; Gilli et al. 2007); could an obscured AGN near the PG1148+549 sight line change the ionizing flux field in a way that boosts the O vi and Ne vii column densities? To explore this idea, we have used CLOUDY to produce models of an obscured AGN with obscuring columns as high as log N(H i) = 23. Our absorbers are optically thin and thus are always exposed to the UV background, so we combined the flux from the obscured AGN with the Haardt & Madau UV background with various mixtures of relative brightness of the two components of the model. Every variation of this obscured AGN + UV background model failed badly. As can be seen in, e.g., Figure 1(d) of Hamann (1997), obscuration of an AGN actually reduces the flux of photons capable of photoionizing Ne vii to produce Ne vii more than it reduces the flux that can ionize O ii, O iii, O iv, etc., so adding an obscured AGN does not boost the Ne vii or O vii column densities relative to the lower ionization stages.

It appears that the Ne vii and O vii must arise in a separate gas phase from the lower ionization stages. But is the Ne vii-bearing gas photoionized or collisionally ionized? We can rule out photoionized Ne vii and O vii—our CLOUDY models indicate that in order to arise in photoionized gas, the observed Ne vii and O vii columns would require very high values for U. With the Haardt & Madau flux at z = 0.68, this in turn requires very low densities and cloud sizes > 1 Mpc. Such large sizes would result in broadening of the lines by the Hubble flow that is not allowed by the measured line widths. Similar arguments have been made for other systems with Ne vii detections, where the implied cloud sizes in the photoionized Ne vii models lead to unrealistically large cloud sizes (Savage et al. 2005; Narayanan et al. 2011, 2012; Tripp et al. 2011).

As single-phase and two-phase photoionization models fail to account for both the low and high ions simultaneously, we conclude that the lower ions (O iii, C iii, O iv, etc.) reside in a photoionized core, and that the high ions (O vi and Ne vii) reside in a collisionally ionized, hot phase. Such necessity of a collisionally ionized phase has also been demonstrated for other Ne vii absorbers (Narayanan et al. 2009, 2011, 2012; Savage et al. 2005; Tripp et al. 2011). We will investigate the implied properties of the hot phase in Section 5.2.

We have applied the same photoionization models to the component at v = 40 km s\(^{-1}\) in the z\(_{\text{abs}}\) = 0.68381 absorption system. As summarized in Table 8, we obtain very similar results as we found for the v = 0 km s\(^{-1}\) component, including the same overall metallicity (Z = 0.3 Z\(_{\odot}\)), similar underabundances of carbon and nitrogen (relative to oxygen), and a similar ionization parameter.

5.1.2. z\(_{\text{abs}}\) = 0.70152 and 0.72478

We have used our CLOUDY photoionization models to similarly constrain the properties of the systems at z\(_{\text{abs}}\) = 0.70152 and 0.72478, and our results are listed in Table 8. For these absorption systems, we only have upper limits on the H i column density and we detect a more limited suite of metals, but we can, nevertheless, show that the physical conditions and metallicity are similar to those of the z\(_{\text{abs}}\) = 0.68381 system.

For the v = 0 km s\(^{-1}\) component of the z\(_{\text{abs}}\) = 0.70152 absorber, the observed O iv/O iii ratio indicates that log U = −1.38 and, interestingly, the observed columns require a supersolar metallicity, [X/H] > +0.2. We can only place a lower limit on the metallicity since we only have an upper limit on N(H i);
a decrease in the \(N(H\text{ I})\) assumed for the photoionization model [\(\log(N(H\text{ I})) \leq 13.60\)] would require an increase in the metallicity. However, in this component the evidence for a carbon under-abundance is less compelling with \([C/O] = -0.1\), and we have no information about nitrogen. On the other hand, we once again draw a robust conclusion about the highly ionized gas: the \(O\text{ vii} \) and \(Ne\text{ viii} \) column densities are orders of magnitude higher than expected in photoionization models—these models cannot simultaneously match \(O\text{ iii}, O\text{ iv}, O\text{ vi}, \) and \(Ne\text{ viii} \) in a single-phase gas cloud.

Due to blending, we are unable to measure \(N(O\text{ iii})\) in the \(v = 59\) km s\(^{-1}\) component of the \(z_{abs} = 0.70152\) system (see Figure 4), which leads to greater ambiguity in the modeling. We bracket the physical conditions and metallicity in this component by considering two photoionization models that are at the extreme ends of the ionization parameter range allowed by the data. These models are referred to as Model 1 and Model 2 in Table 8. In Model 1, we find the ionization parameter that matches the observed minimum \(O\text{ iv}/O\text{ iii} \) ratio (based on the measured \(N(O\text{ iv})\) and the upper limit on \(N(O\text{ iii})\)). As in the previous section, this model falls far short of the observed \(N(O\text{ vi})\). In Model 2, we find the value of \(U\) that matches the observed \(O\text{ iv}/O\text{ vi} \) ratio. By definition, Model 2 agrees with the measured \(N(O\text{ vi})\), but we note that this model does not produce enough \(Ne\text{ viii} \) compared to the observations.

While it only provides a lower limit on \(U\), we argue that Model 1 is likely closer to the actual physical conditions and metallicity of the gas for the following reasons. First, Model 2 does not predict enough \(C\text{ iii} \) compared to the measured \(N(C\text{ iii})\), and in order to fit the data, we must invoke a substantial carbon overabundance. There is astrophysical precedence for a carbon underabundance—carbon underabundances are observed in stars in the disk and halo of the Milky Way (Ackerman et al. 2004; Bensby & Feltzing 2006; Fabbian et al. 2009) as well as damped Ly\(\alpha\) absorbers (Pettini et al. 2008; Penprase et al. 2010; Cooke et al. 2011). On the other hand, the combination of low metallicity and a high carbon overabundance required by Model 2, \([X/H] = -0.8\) and \([C/O] = +0.5\), is a rather peculiar abundance pattern. There are some "carbon-enhanced" damped Ly\(\alpha\) systems (Cooke et al. 2012), but these absorbers have much lower metallicities than Model 2. It seems likely that Model 2 requires a carbon overabundance because the model is wrong. Second, as shown in Table 8, Model 1 implies absorber properties (e.g., density and size) that are similar to the characteristics of the other components where \(O\text{ iii}\) is detected, whereas Model 2 requires much lower densities and much larger gas clouds. Third, if we generally place the \(O\text{ vi}\) in the same (cospatial) gas as the \(O\text{ iv}\), then it becomes hard to explain where the \(Ne\text{ viii}\) arises (\(Ne\text{ viii}\) must then originate in a phase that makes no contribution to the \(O\text{ vi}\) column density). If we place the \(O\text{ vi}\) in the \(Ne\text{ viii}\)-bearing gas, which is distinct from the \(O\text{ iv}\) phase, then the \(Ne\text{ viii}\) is naturally explained, as we discuss below. At any rate, Models 1 and 2 bracket the allowed range of physical conditions, as summarized in Table 8.

The \(Ne\text{ viii}\) absorber at \(z_{abs} = 0.72478\) is very similar to the absorption system at \(z_{abs} = 0.70152\), and we have modeled the \(z_{abs} = 0.72478\) system in the same way as we treated the absorber at \(z_{abs} = 0.70152\). Our results for the \(z_{abs} = 0.72478\) case are summarized in Table 8. As in the other systems studied in this paper, the \(z_{abs} = 0.72478\) requires a high metallicity, as one might expect given the detection of metals and the absence of \(H\text{ i}\) (Figure 7), and the presence of \(Ne\text{ viii}\) requires a hot, collisionally ionized phase.

### 5.2. Collisional Ionization

The photoionization models fail to produce enough \(O\text{ vi}\) and \(Ne\text{ viii}\) to match the observed column densities because the required gas densities are too low and the cloud sizes are too large. Consequently, we now consider whether addition of a hot, collisionally ionized phase provides a viable explanation of the \(O\text{ vi}\) and \(Ne\text{ viii}\). To predict column densities of various ions as a function of temperature, we employ the ion fractions in collisionally ionized gas from Gnat & Sternberg (2007); we mainly assume that the gas is in CIE, but we provide some brief comments on how the results can change if the absorption arises in non-equilibrium, rapidly cooling gas. We also must make assumptions about the metallicity and total \(H\text{ I} + H\text{ II}\) column density of the absorbing gas \(N(H\text{ tot})\). The profiles of \(O\text{ iii}, O\text{ iv}, O\text{ vi}, \) and \(Ne\text{ viii}\) are all well aligned in velocity space and there is clearly some type of relationship between the \(Ne\text{ viii}\) phase and the lower-ionization material, so we assume that the hot gas has the same metallicity as the photoionized gas. With that assumption, we find the gas temperature that matches the \(Ne\text{ vii}/O\text{ vi}\) ratio and adjust \(N(H\text{ tot})\) to fit the observed columns of the metals. Table 9 lists the results of this procedure (in the CIE case) for the \(v = 0\) km s\(^{-1}\) components of the absorbers at \(z_{abs} = 0.68381, 0.70152,\) and 0.72478, including the derived temperature and \(N(H\text{ tot})\) as well as the predicted column density of \(H\text{ i}\) in the hot gas and the \(H\text{ i}\) Doppler parameter.

As an example, Figure 11 shows the predicted CIE column densities of several relevant ionization stages in the \(v = 0\) km s\(^{-1}\) component of the \(Ne\text{ viii}\) absorber at \(z_{abs} = 0.68381\). These hot-gas models have several notable features. First, all of the observed column densities, as well as upper limits on undetected species, are fully consistent with a combination of a hot-gas phase (the source of \(O\text{ vi}\) and \(Ne\text{ viii}\)) and a distinct photoionized (cool) gas phase (the source of all other detected species). In the \(v = 0\) km s\(^{-1}\) component at \(z_{abs} = 0.68381,\) the \(Ne\text{ viii}/O\text{ vi}\) ratio requires a gas temperature of \(T = 10^{5.7}\) K. At this temperature, the predicted \(S\text{ v}\) and \(S\text{ vi}\) column densities from the hot gas are both below the observed upper limits. The \(O\text{ iv}\) and \(C\text{ iii}\) columns

### Table 9

Properties of the Collisionally Ionized Hot Phase of the PG1148+549 \(Ne\text{ viii}\) Absorbers

| Redshift  | Log \([T\text{ (K)}]\) | Log \([N(H\text{ tot})\text{ (cm}^{-2}\text{)\text{a}}]\) | Log \([N(H\text{ (i)})\text{ (cm}^{-2}\text{)\text{a}}]\) | \(b\text{ (km}\text{ s}^{-1}\) |
|-----------|----------------------|---------------------------------|---------------------------------|-----------------|
| 0.68381...| 5.69                 | 19.8                             | 13.6                             | 90               |
| 0.70152...| 5.69                 | <19.0                            | <12.8                            | 90               |
| 0.72478...| 5.72                 | <18.9                            | <12.6                            | 93               |

**Notes.**

\(\text{a}\) The predicted neutral hydrogen column density given the inferred temperature and \(N(H\text{ tot})\) (see text).

\(\text{b}\) The predicted Doppler parameter for hydrogen at the given temperature.

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from the hot gas are also extremely low, so we can legitimately assume that the O iv and C iii absorption only arises in the cool, photoionized phase.

On the other hand, we see from Figure 11 that even though the Ne viii-bearing gas is hot, it does contain an appreciable amount of H i (thin black line in Figure 11): the hot-gas model predicts log N(H i) = 13.6 for this component at the inferred temperature and assumed metallicity. However, H i lines arising in the hot phase will also be extremely broad \( b = \sqrt{2kT/m} \) as indicated in Table 9, and this makes detection of the broad H i absorption challenging. Our COS spectrum does not cover the Lyα line at the redshifts of the Ne viii absorbers, and the broad Lyβ line predicted by the model in Figure 11 is too weak to be detected in our data. Future observations of the Lyα line could, in principle, detect the predicted broad Lyα line and thereby corroborate our hot-gas detection. Moreover, this would provide additional information—the combined analysis of \( b \)-values of low-mass and high-mass elements constrains the non-thermal line broadening (e.g., due to turbulence) as well as the temperature (see Section 4.1.1 in Tripp et al. 2008). So, while we have a good estimate of the gas temperature of the hot phase of the Ne viii absorbers, it would still be worthwhile to observe the Lyα line to obtain more insight. Absorption systems showing evidence of broad Lyα plus narrower O iv and/or Ne viii have been identified previously (Tripp et al. 2001; Richter et al. 2004; Narayanan et al. 2010, 2012; Savage et al. 2011a, 2011b), and analysis of well-aligned H i and O iv absorption lines indicates that non-thermal broadening is important (Tripp et al. 2008).

We do not yet have the ability to apply such an analysis to the systems in this paper, but we can at least check that if the Doppler parameters that the metal lines provide are consistent with gas temperatures implied by the Ne viii/O iv ratios. For log \( T \approx 5.7 \) K, as indicated by the Ne viii/O iv ratios in these systems, the Doppler parameters from thermal broadening are \( b(O iv) = 22.7 \text{ km s}^{-1} \) and \( b(\text{Ne viii}) = 20.6 \text{ km s}^{-1} \). The observed Doppler parameters for all of the Ne viii lines in these systems are in agreement with this constraint. The best-fit Doppler parameters for the O iv \( \lambda 1031.93, 1037.62 \) lines in the \( z_{abs} = 0.68381 \) and \( z_{abs} = 0.70152 \) systems are also consistent with the expected line width. The O iv line width in the \( z_{abs} = 0.72478 \) system (which suffers from particularly noisy profiles) is slightly more discrepant with the expected line width but is still consistent within 2\( \sigma \).

Finally, comparing the total hydrogen column densities derived for the hot gas versus the photoionized, cool gas (compare Tables 8 and 9), we see that total hydrogen column densities are generally more than an order of magnitude higher in the hot gas than in the cool gas, and therefore the hot (Ne viii) phase likely contains substantially more mass than the photoionized gas. This is similar to the preponderance of hot gas found by Tripp et al. (2011) in a multiphase Ne viii absorber affiliated with a post-starburst galaxy. This conclusion rests on the assumption that the metallicity of the hot phase is roughly the same as the metallicity of the cool phase. If the hot phase has a higher metallicity, it will have a lower total hydrogen column, but we note that even if the hot phase metallicity is ten times higher than that of the cool phase, the hot gas will still harbor a similar total hydrogen column density. It has been suggested that in general, the cool circumgalactic gas detected in QSO absorbers is an important baryon reservoir (Werk et al. 2013), and it appears that there is just as much mass (or more) in the hot gas traced by Ne viii.

We have also considered the non-equilibrium collisional ionization models of Gnat & Sternberg (2007). Again, with these models we find that no single-phase model can account for the observed ratios and columns of O iii, O iv, O vi, and Ne viii—the non-equilibrium models also require a distinct, hot phase. In general, the non-equilibrium models yield similar results for the hot phase but can fit the observed column densities at a slightly lower temperature (see, e.g., Figure S5 in Tripp et al. 2011). It is possible that the O vi \( b \)-value in the system at \( z_{abs} = 0.72478 \), which is somewhat more narrow than expected based on the CIE model, favors a non-equilibrium situation. However,
Table 10
Spectroscopic Properties of Galaxies near PG1148+549

| Galaxy ID  | z_{gal}  | Impact Parameter (kpc) | Star Formation Rate (M_{\odot} yr^{-1}) | M_{\star}^{c} | [O/H]^{b} |
|------------|----------|------------------------|-----------------------------------------|--------------|----------|
| 76.24…    | 0.25250  | 95                     | 1.53 ± 0.04                             | −19.86 ± 0.04| −0.11 ± 0.15|
| 142.30…   | 0.72492  | 217                    | 6.42 ± 0.44                             | −21.15 ± 0.13| +0.22 ± 0.15|

Notes.

a The first number in the galaxy identifier is the position angle (north through east) in degrees, and the second number is the angular separation from the QSO in arcseconds.

b Star formation rate and logarithmic metallicity measured as described in Werk et al. (2012).

c R-band absolute magnitude.

One of the LRIS galaxies (76.24) is at a low enough redshift (z_{gal} = 0.2525) so that we cannot check for affiliated Ne VIII, but we note that the COS spectrum shows strong O VI, C III, and multiple H I Lyman series absorption lines at this redshift, consistent with recent findings that strong O VI absorption is ubiquitous in the halos of star-forming galaxies (Prochaska et al. 2011; Tumlinson et al. 2011a). The other LRIS galaxy (142.30) is only Δv ≈ +30 km s^{-1} from the Ne VIII absorber at z_{abs} = 0.72478. In many regards, Galaxy 142.30 has the characteristics one might expect to find for an object embedded in a gas-rich halo: the galaxy is luminous (L ∼ L^∗), has a high metallicity ([O/H] = +0.22 ± 0.15), and a relatively high SFR of 6.42 ± 0.44 M_{\odot} yr^{-1}. However, the galaxy has one surprising feature: it is fairly far from the sight line (impact parameter = 217 kpc). Given the high metallicity of the affiliated absorber, Z > Z_{\odot}, the relatively large distance to the nearest galaxy is notable, although we stress that more galaxy redshift measurements are required to thoroughly probe the origin of this absorbing gas.

7. DISCUSSION

7.1. Redshift Density and Baryonic Content

One of the primary goals of our COS survey is to provide some basic statistics on Ne VIII QSO absorption systems such as the number of these systems per unit redshift, dN/dz. The Ne VIII absorption lines are weak, and at the redshifts where they can be observed with HST, there is a moderately high density of absorption lines from other redshifts, so discovery of the Ne VIII absorbers is slow work that requires careful identification of all of the lines in a spectrum (not just the Ne VIII) to avoid spurious misidentifications. This work is underway, but we can obtain some preliminary statistics based on the PG1148+549 data.

The COS spectrum of PG1148+549 enables detection of the redshifted Ne VIII λλ770.41, 780.32 lines above z = 0.49. Here we are mainly interested in the circumgalactic gas in the large halos of intervening galaxies. It is known that there is a statistically significant excess of highly ionized absorbers with z_{abs} ≈ z_{QSO} (see, e.g., Figures 14 and 15 in Tripp et al. 2008), many of which arise in AGN-driven outflows and other phenomena that occur quite close to the central engine of AGNs (e.g., Ganguly & Brotherton 2008). For this reason, we excluded the region within 3000 km s^{-1} of z_{QSO} from the part of the PG1148+549 spectrum that we probed for Ne VIII absorption. Following the method outlined in Tripp et al. (2008) to account for variable S/N and regions blocked by strong lines from other redshifts, we find that the total redshift over which we can detect Ne VIII is Δz = 0.43 for a 10-pixel wide line and a minimum detection threshold of 30 mÅ. In terms of the

Figure 12. Deep U-band image of the PG1148+549 field from the Large Binocular Telescope. The image is centered on the QSO. Galaxies for which we have obtained spectroscopic redshifts with Keck/LRIS are marked with a 10′′ box. The label above each box is our galaxy identification code; the first number in the galaxy ID label is the position angle (north through east) from the QSO (in degrees), and the second number is the angular separation from the QSO (in arcseconds).

higher S/N measurement of the line width is needed before this can be considered to be strong evidence.

6. AFFILIATED GALAXIES

To begin to probe the relationships between the PG1148+549 Ne VIII absorbers and nearby galaxies, we have obtained deep imaging and spectroscopy, as summarized in Section 2. Figure 12 shows our U-band LBT image of the PG1148+549 field, which has a 5σ limiting magnitude of U_{AB} = 26.0. We obtained Keck/LRIS spectra of the four brightest objects near the sight line. The LRIS spectra showed that two of the LRIS targets are galaxies at interesting redshifts. These galaxies are labeled in Figure 12 by their position angle from the QSO (north through east) and their angular separation from the sight line. As described in Werk et al. (2012), we have estimated the SFRs, H II-region metallicities, absolute magnitudes, and impact parameters of the galaxies observed with LRIS. These properties are presented in Table 10, and the spectrum of galaxy 142.30 is shown in Figure 13.
Figure 13. Keck/LRIS spectrum of the galaxy 142_30 (see Figure 12). Several emission lines are evident including Balmer lines, \([\text{O}\ ii]\), and \([\text{O}\ iii]\), and these features indicate a vacuum Heliocentric redshift of \(z_{\text{em}} = 0.72492\). The emission lines also provide constraints on the SFR and metallicity of the galaxy (see Table 10). The cyan line below the spectrum represents the \(1\sigma\) uncertainty in the flux.

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

comoving “absorption distance” (Bahcall & Peebles 1969),

\[
dX = \frac{H_0}{H(z)} (1 + z)^2 dz,
\]

where \(H_0\) is the Hubble constant and \(H(z) = H_0 \sqrt{\Omega_m (1 + z)^3 + \Omega_{\Lambda}}\) in our adopted cosmology, we can detect Ne\ viii over a total comoving path of \(\Delta X = 0.87\).

With these numbers, we obtain \(dN/dz = 7\pm4\) for Ne\ viii absorbers with \(W_0 > 30\) mÅ or, in terms of the comoving path, \(dN/dX = 3\pm1\), with uncertainties from Poisson statistics (Gehrels 1986). This estimate will be revised in future work when all of the spectra from this program will be analyzed and presented. We note that the O\ vii\ \(\lambda 1031.93\) lines affiliated with these Ne\ viii absorbers have rest equivalent widths greater than 70 mÅ, and the \(dN/dz\) of O\ vi absorbers with \(W_0 > 70\) mÅ (Tripp et al. 2008; Tilton et al. 2012) is similar to the \(dN/dz\) that we find for Ne\ viii.

We can also estimate the cosmological mass density, \(\Omega \equiv \rho/\rho_c\), traced by the Ne\ viii absorbers. The cosmological mass in the form of Ne\ viii ions only is

\[
\Omega_{\text{Ne\ viii}} = \frac{H_0 m_{\text{Ne}}}{c \rho_c} \frac{\sum N_i (\text{Ne\ viii})}{\Delta X},
\]

where \(m_{\text{Ne}}\) is the mass of neon and \(\rho_c\) is the critical density. Summing over the Ne\ viii absorbers discussed above, we obtain

\[\Omega_{\text{Ne\ viii}} \approx 6 \times 10^{-8}.
\]

The mass in Ne\ viii ions is tiny, but for some questions, this quantity is a useful constraint. Most of the mass in these absorbers is, of course, in the ionized hydrogen, which can only be estimated with models that constrain the hydrogen ionization correction. For this purpose, we use the hot-gas results presented in Table 9, and we calculate the total baryonic mass in the Ne\ viii systems using

\[
\Omega_b = \frac{H_0 \mu m_{\text{H}}}{c \rho_c} \frac{\sum N_i (\text{H}_{\text{tot}})}{\Delta X},
\]

where \(m_{\text{H}}\) is the hydrogen mass and we assume \(\mu = 1.3\) to account for mass in helium. From the total hydrogen column densities in Table 9 and this expression we find

\[\Omega_b \lesssim 0.002.
\]

This is an upper limit because two of the Ne\ viii systems provide only upper limits on \(N(\text{H}i)\) and \(N(\text{H}_{\text{tot}})\). It is interesting to note that this upper limit amounts to \(\approx 4\%\) of the baryons (Spergel et al. 2007), but we emphasize that both \(\Omega_{\text{Ne\ viii}}\) and \(\Omega_b\) are still quite uncertain due to the small sample and uncertainty in the metallicity\(^\text{12}\) of the Ne\ viii-bearing gas. We will revisit these quantities in a future paper when our full sample has been analyzed.

\(^\text{12}\) The \(N(\text{H}_{\text{tot}})\) derived from the models depends on the adopted metallicity of the Ne\ viii-bearing gas, which we have assumed is the same as the well-constrained cooler, photonized gas in each absorber. If the Ne\ viii phase tends to be more mixed with lower-metallicity ambient gas, then the metallicity of the Ne\ viii could be lower, which would increase \(N(\text{H}_{\text{tot}})\) and \(\Omega_b\). Conversely, if the hot gas (including the Ne\ viii) tends to separate from the cooler gas (as occurs in some models, e.g., Mac Low & Ferrara 1999), then the Ne\ viii gas could have higher metallicity.
In addition to the large uncertainty due to the small sample, we note one curious aspect of the PG1148+549 Ne \textsc{viii} absorbers: while our data have sufficient S/N to detect these lines over a large redshift range (0.51 \leq z \leq 0.96), all of the Ne \textsc{viii} systems that we identify are clustered in a small portion of this redshift window with 0.68381 \leq z_{\text{abs}} \leq 0.72478. This raises a question: could the three absorption systems be related somehow? For example, could these absorbers all be ejecta from a single galaxy? This seems unlikely because the absorber redshifts are spread over a large velocity range (7200 km s^{-1}). Outflows driven by quasars (e.g., broad absorption-line outflows) do attain such velocities, but usually these outflows exhibit many adjacent components spread over the velocity range, or they show a smooth but very broad absorption trough extending over a large velocity interval (see, e.g., Capellupo et al. 2012). The PG1148+549 Ne \textsc{viii} absorbers have no resemblance to BAL outflows. Some quasars have been shown to have absorption systems due to QSO ejecta that are highly displaced in redshift from the QSO (e.g., Jannuzi et al. 1996; Bowen et al. 2001; Rodríguez Hidalgo et al. 2011), but these also show distinctive characteristics (e.g., relatively broad and smooth absorption profiles) that do not match the PG1148+549 Ne \textsc{viii} systems.

It seems improbable that these Ne \textsc{viii} absorbers originate in an outflow from a single galaxy. A more plausible explanation is that the sight line passes through a region with a relatively high density of gas-rich, star-forming galaxies at \( z \approx 0.7 \), and each of the three absorbers originate from separate galaxies. This is a testable hypothesis, and we are obtaining additional deep, multiobject spectroscopy of a large number of galaxies in the PG1148+549 field which could reveal such a large-scale structure. This spectroscopic survey is underway but not yet complete; once this has been completed, we will reexamine the origins of these Ne \textsc{viii} systems. The existence of such a structure on this line of sight could bias the redshift density and baryonic content estimates. Incorporation of a larger number of sight lines is necessary to reduce the effects of this type of cosmic variance, and analysis of these statistics with larger numbers of sight lines is underway.

7.2. Cross Section, Size, and Stability

The redshift density (\( dN/dz \)) of the Ne \textsc{viii} absorbers can be interpreted in a variety of ways. Frequently, \( dN/dz \) is used to estimate an effective cross section (\( \pi R^2 \)) of absorption systems:

\[
dN/dz = n_{\text{abs}} \pi R^2 \frac{c}{H(z)}(1+z)^2, \tag{4}
\]

where \( n_{\text{abs}} \) is the spatial (volume) density (number per Mpc) of the absorbing entities (not the particle density). While we have an approximate determination of the product of \( n_{\text{abs}} \) and \( \pi R^2 \), we do not know the values of these quantities individually. Nevertheless, we have derived constraints on the thickness of the low-ionization component of the absorbers (final column of Table 8)—the photoionization models imply that the low-ionization phase has a thickness ranging from less than 100 pc up to 3.5 kpc. It is important to note that all of the intervening Ne \textsc{viii} absorbers in the PG1148+549 sight line and all of the Ne \textsc{viii} absorbers from other sight lines reported in the literature show well-detected lower-ionization absorption lines that are well aligned with the Ne \textsc{viii}. Therefore, it appears that the cross section of the Ne \textsc{viii} and the lower ionization stages are the same—in order to detect Ne \textsc{viii}, it has (so far) always been necessary for the sight line to pierce the lower-ionization cloud as well. If we assume, based on the sizes derived for the lower ionization phases, that the clouds have a typical diameter of 1 kpc and we solve Equation (4) for the space density, we find that \( n_{\text{abs}} \approx 1100 \text{ Mpc}^{-3} \). This number is highly uncertain; just considering the 1\sigma uncertainty in \( dN/dz \), \( n_{\text{abs}} \) could range from \( \approx 500 \) up to \( 2000 \text{ Mpc}^{-3} \). Nevertheless, even with these uncertainties, \( n_{\text{abs}} \) for these absorbers is vastly larger than the space density of galaxies at \( z \approx 0.7 \). Integrating the galaxy luminosity functions from the DEEP2 or VVDS surveys (Willmer et al. 2006; Ilbert et al. 2005) indicates that galaxies with \( L \geq 0.1 L^* \) have a space density of \( n \approx 10^{-2} \) at this redshift. Previous studies provide strong evidence that O \textsc{vi} absorbers are affiliated with galaxies (Stocke et al. 2006; Prochaska et al. 2011; Tumlinson et al. 2011a), but their statistics require >10^4 analogous clouds per galaxy to explain the observed \( dN/dz \). This requirement for a large number of clouds per galaxy has been noted for other types of QSO absorbers including weak Mg \textsc{ii} systems at similar redshifts (Ribgy et al. 2002) and metal-rich C\textsc{iv} absorbers at higher redshifts (Schaye et al. 2007). An important caveat in this calculation is that the density of the photoionized gas, and hence the absorber thickness, depends on the assumed intensity of the photoionizing flux. While models of the UV background and observational constraints on its intensity appear to be in broad agreement (see, e.g., Figure 7 in Davé & Tripp 2001), it is possible that there is substantial spatial variability of the UV background flux or systematic errors in its estimation, and this could affect our estimate of \( n_{\text{abs}} \). Indeed, detection of Ne \textsc{viii} may introduce a bias if these absorbers are more likely to arise in regions of elevated flux. However, even with this uncertainty, it seems likely that any plausible UV ionizing flux will require \( n_{\text{abs}} > n_{\text{gal}} \).

Alternatively, we can turn this around and ask: if the Ne \textsc{viii} absorbers are affiliated with some type of galaxy of known spatial density \( n_{\text{gal}} \), what is the effective cross section of the Ne \textsc{viii}-bearing gas that produces the observed \( dN/dz \)? Tumlinson & Fang (2005) used this argument to show that if low-\( z \) O \textsc{vi} absorbers originate in faint/dwarf galaxies, then metals must be transported to distances of \( \approx 200 \) kpc from their galaxies of origin (if these metals come from \( L^* \) galaxies, they must be transported even farther). As noted above, galaxies with \( L \geq 0.1 L^* \) have a spatial density of \( n_{\text{gal}} \approx 10^{-2} \text{ Mpc}^{-3} \) at \( z = 0.7 \). Equating this value of \( n_{\text{gal}} \) to \( n_{\text{abs}} \) in Equation (4), we obtain \( R \approx 100–200 \text{ kpc} \), where the range reflects the uncertainty in \( dN/dz \). Here we have assumed that the covering fraction of the Ne \textsc{viii} systems is \( \approx 1 \); if the covering fraction is smaller, then the effective cross section must be even larger. While this is a rough initial estimate, this implies a large transport distance for such metal-rich gas. How is solar-metallicity gas propagated to such a large distance? We note that the frequency of Ne \textsc{viii} absorbers may indicate that they are more likely to be connected with lower-luminosity dwarf galaxies, based on an argument analogous to the one applied by Tumlinson & Fang (2005) to the O \textsc{vi} systems: if the Ne \textsc{viii} absorbers originate in \( L^* \) galaxies, then they must have very large effective cross sections that seem improbable. If we only consider galaxies with \( L \geq 1.0 L^* \), for example, then the galaxy density drops to \( n_{\text{gal}} \approx 10^{-3} \), which requires an effective cross section \( \geq 1 \text{ Mpc} \). The finding of Mulchaey & Chen (2009) and Chen & Mulchaey (2009) that lower-redshift Ne \textsc{viii} absorbers are affiliated with sub-\( L^* \) galaxies supports this implication of the statistics.

The arguments above suggest that the Ne \textsc{viii} systems arise in extended gaseous halos that are filled with a large number of small clouds. Would such a configuration be stable? For
the photoionized portions of the absorbers, we can estimate the radial size of the photoionized phase, assuming it is in hydrostatic equilibrium, given the gas temperature, $N(\text{H})$, the fraction of the mass in gas, and the $\text{H}\ I$ photoionization rate (see Equation (12) in Schaye 2001). Assuming typical values for these parameters, we find that the properties of the photoionized gas in Table 8 imply that the radial size of the photoionized cloud is $\sim 60$–100 kpc if it is in hydrostatic equilibrium. For the systems at $z_{\text{abs}} = 0.70152$ and 0.72478, we find that similarly large clouds are expected in hydrostatic equilibrium with sizes $\gtrsim 100$ kpc. In contrast, the photoionization models suggest that the absorbers are vastly smaller (last column in Table 8). This might indicate that the photoionized clouds in this system are not in hydrostatic equilibrium but rather are in the process of expanding and/or evaporating.

Alternatively, they could be pressure-confined by the surrounding medium. The Cloudy models indicate that the pressure in the cool, photoionized phase is $p/k \approx 10^{-3} \text{ K}$. If the Ne $\text{viii}$ phase surrounds and pressure confines the cool gas, then pressure balance requires a particle density of $\approx 10^{-5} \text{ cm}^{-3}$. While this is a reasonable density for halo gas, it may require sizes that are unreasonably large when combined with $N(H_{\text{tot}})$ for the hot gas (see Table 9), and for this reason it is unlikely that the Ne $\text{viii}$ phase pressure confines the cool gas. This is not surprising—the close alignment of the Ne $\text{viii}$ phase with the cooler gas suggests that the Ne $\text{viii}$ arises in an interface between the cool gas and a hotter (unseen) ambient medium; this hypothesis has been favored in analyses of other Ne $\text{viii}$ systems as well (Mulchaey & Chen 2009; Narayanan et al. 2011; Tripp et al. 2011). In this scenario, the absorber is likely not a stable entity but rather is in the process of dissipating into the halo in which it is embedded, e.g., outflow ejecta that is expanding as it moves away from its source.

8. SUMMARY

Using a high-S/N spectrum of the bright QSO PG1148+549 ($z_{\text{QSO}} = 0.9754$) obtained with the COS, we have discovered three new Ne $\text{viii}$ absorption-line systems at redshifts ranging from $z_{\text{abs}} = 0.68381$ to 0.72478. These absorbers exhibit a variety of absorption lines from other metals including C $\text{iii}$, N $\text{iv}$, O $\text{iii}$, O $\text{iv}$, and O $\text{vi}$. In this work we have reported on the physical conditions and ionization of these multiphase Ne $\text{viii}$/O $\text{vi}$ absorbers, and we have discussed the implications of measurements regarding the nature and origin of the absorbers. In summary, our primary conclusions are the following.

1. A single-phase model in which all of the ions are produced via photoionization or collisional ionization fails to reproduce the observed column density ratios; a multiphase absorption system is clearly required to explain the range of detected ions (from O $\text{iii}$ up to Ne $\text{viii}$). Moreover, the O $\text{vi}$ and Ne $\text{viii}$ cannot originate in photoionized plasma—models in which the high ions are produced via photoionization predict unphysically large cloud sizes, with absorption lines that would be highly spread out by broadening in the Hubble flow. We conclude that the O $\text{vi}$ and Ne $\text{viii}$ lines arise in collisionally ionized gas with $T \approx 10^{5.7} \text{ K}$, while the low ions are produced via photoionization.

2. The oxygen abundances of the systems, as determined from the low ions and photoionization modeling, are all $[\text{O}/\text{H}] > -0.5$, higher than the typically assumed metallicity of the CGM/IGM of $[\text{X}/\text{H}] \sim -1.0$. The $z_{\text{abs}} = 0.70152$ and 0.72478 systems require supersolar metallicities. These are abundances in the cool gas, and we assume for our analysis that the hot gas probed by the Ne $\text{viii}$ has a similar metallicity. The hot gas could have a different metallicity than the cool phase, e.g., it could be more metal rich because hot gas tends to separate from the cooler material in outflows (e.g., Mac Low & Ferrara 1999). On the other hand, the metallicity of the major baryon reservoirs in the CGM and IGM may have much lower metallicities and we are not yet detecting those reservoirs; detection of such low-metallicity material in metal absorption lines may require significantly higher S/N spectroscopy.

3. The absorbers also indicate moderate underabundances of carbon and nitrogen (compared to oxygen) at a level similar to the C and N underabundances observed in Milky Way halo stars.

4. Assuming that a portion of the gas is photoionized by the UV background from quasars and galaxies, the ionization models indicate that the low-ionization phase has low density ($\approx 10^{-4} \text{ cm}^{-3}$), small size ($3.5 \text{ kpc}$ down to $<100 \text{ pc}$), and low thermal pressure, $p/k \approx 10^{-3} \text{ K}$. The total (H $\text{i} + \text{H} \text{ii}$) hydrogen column densities in these absorbers range from $<10^{17} \text{ cm}^{-2}$ up to $10^{18.5} \text{ cm}^{-2}$.

5. The hot, collisionally ionized phase that contains O $\text{vii}$ and Ne $\text{viii}$ has $T \approx 10^{5.7} \text{ K}$ based on the O $\text{vii}$ to Ne $\text{viii}$ ratio, assuming CIE. Non-equilibrium models (Gnat & Sternberg 2007) require only slightly lower temperatures. The ionization models indicate that the total hydrogen column density in the hot gas is approximately $10^9$ times larger than the total hydrogen column in the cool, photoionized material.

6. The COS spectrum has sufficient S/N to reveal Ne $\text{viii}$ lines with $W_r > 30 \text{ mA}$ over a total redshift window of $\Delta z = 0.43$ (or a comoving absorption distance $\Delta X = 0.87$), which implies a redshift density of $dN/dz = 7.2^{+3.4}_{-2.0}$ (comoving redshift density $dN/dX = 3.5^{+2.0}_{-0.9}$). The cosmological mass density of the Ne $\text{viii}$ ions is $\Omega_{\text{Ne, viii}} \approx 6 \times 10^{-8}$, and a preliminary constraint on the baryon mass in these absorbers is $\Omega_{\text{b}} \lesssim 0.002$.

7. Given the small sizes implied for the low-ionization phase that is always detected along with the Ne $\text{viii}$, the observed $dN/dz$ indicates that galaxies generally have a large number of these metal-enriched, multiphase clouds in their halos with effective cross sections of 100 kpc or more.

8. However, the clouds are unlikely to be stable and long-lived. The small size of the photoionized phase implies that the clouds will expand and dissipate, and the correlation of the Ne $\text{viii}$ phase with the photoionized phase suggests that the Ne $\text{viii}$ is the transitional layer produced as the cool gas is heated and photoionized, ultimately destined to blend into the hotter ambient halo of the CGM.

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