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Citation

Pachat, S., Narayanan, A., Khaire, V., Savage, B. D., Muzahid, S., & Wakker, B. P. (2017). Detection of two intervening Ne viii absorbers probing warm gas at $z \sim 0.6$. *Monthly Notices Of The Royal Astronomical Society (Issn 0035-8711)*, 471, 792-810.
doi:10.1093/mnras/stx1435

Version: Not Applicable (or Unknown)
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Downloaded from: <https://hdl.handle.net/1887/58971>

Note: To cite this publication please use the final published version (if applicable).

Detection of two intervening Ne VIII absorbers probing warm gas at $z \sim 0.6$

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Accepted 2017 June 7. Received 2017 June 2; in original form 2017 February 16

ABSTRACT

We report on the detection of two Ne VIII absorbers, at $z = 0.61907$ and 0.57052 in the *Hubble Space Telescope*/Cosmic Origins Spectrograph spectrum of background quasars SDSS J080908.13 + 461925.6 and SBS 1122 + 594, respectively. The Ne VIII 770 line is at $\sim 3\sigma$ significance. In both instances, the Ne VIII is found to be tracing gas with $T \gtrsim 10^5$ K, predominantly collisionally ionized, with moderate densities of $n_{\text{H}} \lesssim 10^{-4} \text{ cm}^{-3}$, sub-solar metallicities and total hydrogen column densities of $N(\text{H}) \gtrsim 10^{19} \text{ cm}^{-2}$. In the $z = 0.61907$ absorber, the low, intermediate ions and O VI are consistent with origin in photoionized gas, with the O VI potentially having some contribution from the warm collisional phase traced by Ne VIII. The $z = 0.57052$ system has H I absorption in at least three kinematically distinct components, with one of them having $b(\text{H I}) = 49 \pm 11 \text{ km s}^{-1}$. The intermediate-ionization lines, O VI and Ne VIII, are coincident in velocity with this component. Their different line widths suggest warm temperatures of $T = (0.5\text{--}1.5) \times 10^5$ K. Both absorbers are residing in regions where there are several luminous ($\gtrsim L^*$) galaxies. The absorber at $z = 0.57052$ is within the virial radius of a $2.6L^*$ galaxy, possibly associated with shock-heated circumgalactic material.

Key words: galaxies: haloes – intergalactic medium – quasars: absorption lines – quasars: individual: SDSS J080908.13 + 461925.6 – quasars: individual: SBS 1122 + 594 – cosmology: observations – ultraviolet: general.

1 INTRODUCTION

Throughout cosmic history, $\gtrsim 90$ per cent of the baryons in the Universe have resided outside of galaxies in the diffuse intergalactic and circumgalactic space. Compared to high redshifts ($z \gtrsim 1$), our understanding of the physical state of these baryons is less complete closer to the present epoch. At high redshifts, the photoionized intergalactic gas traced by the forest of Ly α absorption lines seen in the spectrum of background quasars accounts for nearly all of the baryons in the Universe. The Ly α forest corresponds to gas with densities of $n_{\text{H}} \sim 10^{-5} \text{ cm}^{-3}$ (overdensities of $\Delta = \rho/\bar{\rho} \sim 1\text{--}10$) and photoionization temperatures of $T \sim 10^4$ K (Cen et al. 1994; Hernquist et al. 1996; Miralda-Escudé et al. 1996; Rauch et al. 1997; Rauch 1998; Bolton & Becker 2009). These intergalactic baryons were kept ionized ($f_{\text{HI}} = n_{\text{HI}}/n_{\text{H}} \sim 10^{-4}$), and their thermal state was maintained by the far-ultraviolet (far-UV) radiation background shaped by energetic photons escaping from AGNs and star-forming galaxies across the Universe (Miralda-Escudé & Ostriker 1990; Haardt & Madau 1996, 2012; Shull et al. 1999).

With the formation of large-scale structure, significant changes occurred in the phase structure of these intergalactic baryons. From a predominantly photoionized phase at $z \gtrsim 3$, the intergalactic gas evolved into a complex multiphase medium at low z . Large-scale numerical simulations of structure formation offer a clear insight into this process. The simulations, and also analytical estimates based on baryon measures in galaxies, clusters and the intergalactic medium (IGM), predict that as much as 50 per cent of the baryons from the cool photoionized phase at high z transformed into a highly ionized plasma with temperatures of $T \sim 10^5\text{--}10^7$ K and densities of $n_{\text{H}} \sim 10^{-4}\text{--}10^{-5} \text{ cm}^{-3}$ (Persic & Salucci 1992; Cen & Ostriker 1999, 2006; Davé et al. 2001; Valageas, Schaeffer & Silk 2002). The phase change happened from shock heating when baryonic matter, driven by gravitational forces, streamed into dark matter overdensity clumps where galaxies and clusters gradually formed. Simulations suggest these collisionally ionized *warm-hot* baryons to be in regions with densities that are a factor of 1–1000 greater than the cosmic mean density of matter (Cen & Ostriker 1999). At the low end, these overdensities represent the tenuous regions of the IGM and at the high end, they coincide with regions proximate to galaxies. Observing this diffuse *warm-hot* plasma is not just

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important for completing the baryon census at low z , but it can also offer valuable insights into the chemical abundances and multiphase properties of galaxy haloes that are substantial reservoirs of baryons (Maller & Bullock 2004; Fukugita & Peebles 2006).

Finding this shock-heated phase of gas has been a challenge because of its low density, high temperature and correspondingly low levels of gas neutral fraction ($f_{\text{HI}} \sim 10^{-6}$ – 10^{-7}). Absorption line studies of bright quasars in the ultraviolet have been the most successful method for probing this warm-hot diffuse gas. Among the possible absorption lines that are diagnostic of the low densities and high temperatures of the plasma, highly ionized metal species, mainly O VI and Ne VIII, have been in focus because of their relatively strong doublet transitions in the far-UV and their high-ionization properties.

The Ne VIII species is a tracer of collisionally ionized gas with $T \gtrsim 10^5$ K in the IGM as well as in galaxy haloes. Hybrid models that simultaneously include collisional and photoionization processes associate Ne VIII with low-density gas with $n_{\text{H}} \sim 10^{-5} \text{ cm}^{-3}$ at warm temperatures of $T \sim 5 \times 10^5$ K with collisions dominating the ionizations (Narayanan et al. 2011; Tepper-García, Richter & Schaye 2013). However, at those temperatures and moderate densities, the gas can radiatively cool rapidly within time-scales of $t_{\text{cool}} < 10^8$ yr to $T \sim 10^4$ K where photoionization dominates (Hussain et al. 2017). With the updated extragalactic background light (EBL) given by Khaire & Srianand (2015a, hereafter KS15), Hussain et al. (2017) showed that the Ne VIII absorbers are most likely to be tracers of collisionally ionized gas if the gas metallicity is low ($Z < 0.1 Z_{\odot}$) such that the cooling is slow. Instead, if the gas metallicity is high ($Z \gtrsim Z_{\odot}$), there has to be some constant injection of mechanical energy into the system to counter the cooling due to the presence of metals. In other words, if the gas metallicity is near-solar or higher, the Ne VIII absorber can be tracing cooler photoionized gas. Production of Ne VIII through photoionization alone can also happen in the presence of a hard radiation field as in the case of absorbers close to the central engines of quasars (Petitjean & Srianand 1999; Ganguly et al. 2006; Muzahid et al. 2012).

The choice between photoionization and collisional ionization origin is much more divided for O VI class of absorbers. They too can have a dual origin in cooler photoionized gas as well as warmer collisionally ionized medium (Tripp et al. 2008; Oppenheimer & Davé 2009; Tepper-García et al. 2011). In the latter case, the baryonic column density in the absorber is usually at least a factor of 10 more than when the O VI absorber is photoionized. Quasar absorption line surveys have discovered more than 100 O VI absorbers at low z (Tripp, Savage & Jenkins 2000; Savage et al. 2002; Danforth & Shull 2005; Thom & Chen 2008a,b; Tripp et al. 2008; Tumlinson et al. 2011; Savage et al. 2014; Danforth et al. 2016). In a significant number of these cases, the O VI 1031, 1037 lines are found to be consistent with gas at temperature ranging from 10^5 to 10^6 K (Tripp et al. 2000; Howk et al. 2002; Savage et al. 2002, 2014; Danforth & Shull 2008; Lehner et al. 2009; Narayanan, Savage & Wakker 2010a, 2012; Narayanan et al. 2010b; Savage, Lehner & Narayanan 2011; Pachat et al. 2016). Among these are also instances where the warm gas is directly evident (independent of ionization modelling) through the presence of thermally broad Ly α absorption (BLA, $b(\text{H}\alpha) > 40 \text{ km s}^{-1}$) associated with the O VI. Table 5 in Savage et al. (2014) contains a list of 14 O VI systems where the associated BLAs imply log T ranges from 5.0 to 6.14. Their table also includes four additional O VI systems that have BLAs implying log T from 4.7 to 4.8. Additional references to the literature are found in their detailed discussions of the properties of each system.

Compared to the fairly large frequency of incidence of O VI systems, only 10 intervening Ne VIII 770, 780 detections have been

reported thus far (Savage et al. 2005, 2011; Narayanan, Wakker & Savage 2009; Narayanan et al. 2011, 2012; Tripp et al. 2011; Meiring et al. 2013; Hussain et al. 2015; Bordoloi, Heckman & Norman 2016; Qu & Bregman 2016). The low cosmic abundance of neon compared to oxygen ($[\text{Ne}/\text{O}]_{\odot} = -0.76$; Asplund et al. 2009) could be one of the reasons. The Ne VIII absorption appears at very low contrast against the background continuum for typical IGM column densities of $\log[N(\text{H}\text{I}), \text{cm}^{-2}] \sim 14$ – 16 . The discovery of Ne VIII 770, 780 lines with adequate significance therefore requires high-S/N spectroscopic observations in the ultraviolet.

Eight of the 10 Ne VIII detections have come from *Hubble Space Telescope* (HST)/Cosmic Origins Spectrograph (COS) observations. The remaining two are based on data from the *FUSE* satellite (see Table 1 for a summary). In all those instances, except Bordoloi et al. (2016) where ionization models are not discussed, the presence of Ne VIII was decisive in revealing the presence of warm collisionally ionized gas with $T \gtrsim 10^5$ K in an otherwise complex multiphase absorber (however, see Hussain et al. 2017). Moreover, in each case, the Ne VIII warm gas was found to be tracing a significant baryonic column of $N(\text{H}) \gtrsim 10^{19} \text{ cm}^{-2}$. In several cases, weak and broad Ly α absorption (BLA) associated with the Ne VIII gas was consistent with the high-temperature estimate. In this paper, we report on the discovery of two new Ne VIII absorbers at $z \sim 0.6$ towards the background quasars SDSS J080908.13 + 461925.6 and SBS 1122 + 594. Though a detection is clearly evident in the HST/COS spectra, the formal significance of the Ne VIII 770 absorption feature is lower compared to some of the previous instances of Ne VIII detections. Detailed analysis of the absorption systems rules out a photoionization origin for the Ne VIII in either absorber. Using the revised extragalactic ionizing background of KS15, we find the O VI to be consistent with a photoionized origin.

In Section 2, we present information on the COS archival observations of both sightlines and the data analysis techniques used. In Sections 3 and 4, we describe our measurements on the properties of both absorption systems, with emphasis on the Ne VIII lines. The ionization mechanisms, physical properties and chemical abundances of the absorber towards SDSS J080908.13 + 461925.6 are discussed first in Section 5, followed by the absorption system towards SBS 1122 + 594 in Section 6. In Section 7, we present information on the galaxies identified by the Sloan Digital Sky Survey (SDSS) that are coincident in redshift with the absorbers. The main results are summarized in Section 8, which is followed by a brief discussion on Ne VIII absorbers.

2 THE HST/COS DATA

The SDSS J080908.13 + 461925.6 ($z_{\text{em}} = 0.6587$) quasar data presented here are far-UV medium-resolution [instrumental full width at half-maximum (FWHM) $\sim 17 \text{ km s}^{-1}$] spectra retrieved from the HST/COS MAST archive.¹ The instrument capabilities and in-flight performance are described in detail by Froning & Green (2009), Dixon (2010), Osterman et al. (2011) and Green et al. (2012). The observations were carried out in 2010 as part of a COS dwarf galaxy haloes project (PI: Jason Tumlinson, Prop ID: 12248; Bordoloi et al. 2014). The separate science exposures were processed using the STScI CalCOS (v2.17.3) pipeline. The data consist of G130M and G160M grating spectra of 4.9 ks and 3.0 ks integration times, respectively. For each grating setting, there were multiple FP-position exposures. These individual science exposures were combined in flux units weighted by their exposure times using

¹ <https://archive.stsci.edu/>

Table 1. Intervening Ne VIII detections so far. The table is a compilation of all intervening Ne VIII detections so far. Column 4 shows the equivalent width in the rest frame of the absorber, column 5 shows the apparent optical depth measured column densities, column 6 lists the total hydrogen column density (ionized and neutral combined), column 7 shows the temperature reported by the authors for the Ne VIII gas phase and column 8 lists the dominant ionization mechanism for the production of Ne VIII as concluded by the respective authors [see Hussain et al. (2017) for a remodelling of seven of these absorbers using the updated KS15 ionizing background, and the likelihood of a photoionization origin for the Ne VIII at supersolar metallicities].

Line of sight	z_{abs}	Transition	$W_r(\text{m}\text{\AA})$	$\log [N]$	$\log [N(\text{H})]$	$\log T \text{ (K)}$	$[X/\text{H}]$	Origin of Ne VIII
HE 0226–4110	0.2070	Ne VIII 770	32.9 ± 10.5	$13.85^{+0.12}_{-0.17}$	20.06	5.68 ± 0.02	–	Collisional
(Savage et al. 2005)		Ne VIII 780	24.9 ± 10.6	$14.03^{+0.15}_{-0.24}$	–	–	–	
(Savage et al. 2011)		Ne VIII 780	24.9 ± 10.6	$14.03^{+0.15}_{-0.24}$	–	–	–	
		O VI	–	14.38 ± 0.01	–	–	-0.89 ± 0.1	
3C 263	0.325 66	Ne VIII 770	47 ± 11.9	$13.98^{+0.10}_{-0.13}$	–	5.80	–	Collisional
(Narayanan et al. 2009)								
PKS 0405–123	0.4951	Ne VIII 770	45 ± 6	13.96 ± 0.06	19.67	5.70	-0.6 ± 0.3	Collisional
(Narayanan et al. 2011)		Ne VIII 780	29 ± 5	14.08 ± 0.07	–	–	-0.6 ± 0.3	
		O VI 1038	153 ± 5	14.48 ± 0.01	–	–	–	
PG 1148+549	0.6838	Ne VIII 770	51 ± 12	13.98 ± 0.09	19.80	5.69	> -0.5	Collisional
(Meiring et al. 2013)		O VI 1032	234 ± 19	14.47 ± 0.03	–	–	> -0.5	
		O VI 1038	149 ± 23	14.50 ± 0.06	–	–	> -0.5	
	0.7015	Ne VIII 770	28 ± 5	13.75 ± 0.07	19.00	5.69	> -0.2	Collisional
		Ne VIII 780	18 ± 6	13.86 ± 0.11	–	–	> -0.2	
		O VI 1032	168 ± 19	14.29 ± 0.04	–	–	> -0.2	
		O VI 1038	113 ± 19	14.35 ± 0.06	–	–	> -0.2	
	0.7248	Ne VIII 770	26 ± 8	13.70 ± 0.12	18.90	5.72	> 0	Collisional
		Ne VIII 780	19 ± 5	13.87 ± 0.10	–	–	> 0	
		O VI 1032	71 ± 20	13.84 ± 0.10	–	–	> 0	
		O VI 1038	37 ± 12	13.87 ± 0.15	–	–	> 0	
PG 1407+265	0.5996	Ne VIII 780	52.8 ± 6.6	14.15 ± 0.18	19.40	4.80	> 0	Photoionization
(Hussain et al. 2015)		O VI	–	14.57 ± 0.05	–	–	–	
LBQS 1435–0134	1.1912	Ne VIII	–	13.96 ± 0.17	19.92	–	0.3	Collisional
(Qu & Bregman 2016)		O VI	–	14.49 ± 0.05	–	–	–	
PG 1206+459	0.927	Ne VIII comp-1	–	13.71 ± 0.29	19.4	5.4	3	Collisional
(Tripp et al. 2011)		Ne VIII comp-2	–	14.08 ± 0.08	20.3	5.6	1	
		Ne VIII comp-3	–	14.07 ± 0.04	–	–	0.5	
		Ne VIII comp-4	–	14.53 ± 0.04	20.4	5.6	1	
		Ne VIII comp-5	–	14.21 ± 0.05	–	–	–	
		Ne VIII comp-6	–	13.30 ± 0.27	–	–	–	
		Ne VIII comp-7	–	13.78 ± 0.09	–	–	–	
QSO J1154+4635		Ne VIII 770	–	14.65 ± 0.08	–	–	–	
(Bordoloi et al. 2016)		O VI	–	14.71 ± 0.01	–	–	–	
SDSS J080908+	0.61907	Ne VIII 770	28 ± 8	13.76 ± 0.14	20.45	> 5.6	< 0.5	Collisional
461925.6 (this work)		O VI 1038	248 ± 18	14.79 ± 0.06	–	–	–	
SBS 1122 + 594 (this work)	0.570 52	Ne VIII 770	26 ± 9	13.72 ± 0.15	19.70	5.0	< -0.8	Collisional
		O VI 1032	82 ± 21	13.92 ± 0.13	–	–	-1.4	

the co-addition routine developed by Charles Danforth² and as described in Danforth et al. (2010). The pipeline reduced COS spectra are oversampled at 6 pixels per 17 km s⁻¹ resolution element. The spectra were therefore binned to the optimal Nyquist sampling of 2 pixels per resolution element. The resultant fully combined spectrum has an S/N ~ 10 –20 pixel⁻¹ over much of the wavelength range between 1135 and 1790 Å. The spectral resolution of COS is wavelength dependent with a maximum of $R = \lambda/\Delta\lambda \sim 20\,000$ at near-UV wavelengths and decreasing monotonically to values of $R \sim 17\,000$ at the edge of the far-UV covered by the G130M grating. The spectra were continuum normalized by fitting lower order

polynomials across wavelength intervals of approximately 20 Å, avoiding regions containing absorption or strong emission features.

The SBS 1122 + 594 ($z_{\text{em}} = 0.8514$) COS individual exposures were also retrieved and processed in a similar manner. The quasar was observed for 9.8 ks with the COS G130M grating and 10.5 ks with G160M grating settings. Under each grating setting, multiple exposures with different central wavelengths were used for covering the wavelength gap between the two detector segments of the instrument. The co-added spectrum has continuous wavelength coverage in the range 1135–1790 Å. The Nyquist sampled spectrum has S/N varying in the range 5–15 pixel⁻¹, with the peak S/N occurring at $\lambda \sim 1200$ Å, which is incidentally close to the redshifted location of Ne VIII 770, 780 lines in the absorber identified along this sightline. For both sightlines, our co-added version of the spectra agrees with

² <http://casa.colorado.edu/~danforth/science/cos/costools.html>

the independent extraction method of Bart Wakker, discussed in the appendix of Wakker et al. (2015).

3 THE $z = 0.61907$ ABSORBER TOWARDS SDSS J080908.13 + 461925.6

The continuum normalized regions of the COS spectrum covering important transitions of the absorber at $z = 0.61907$ are shown in Fig. 1. The absorption system has H I Lyman series ($\text{Ly}\alpha - \text{H I } 915$), C II 903.9, 903.6, C III 977, N III 990, N IV 765, O III 702, 833, O IV 788, O VI 1038, S IV 748, S V 786, S VI 933, 945 and Ne VIII 770 lines detected at $\geq 3\sigma$ significance. In addition, the spectrum also covers O II 834, N II 916 and Ne VIII 780, which are non-detections. For the lines that are not detected, we quote the 3σ upper limit by integrating the spectrum through the same velocity range over which O VI is detected.

The absorber is displaced from the systemic redshift of the quasar ($z_{\text{em}} = 0.6587$; Hewett & Wild 2010) by $\Delta v = -7252 \text{ km s}^{-1}$, which is beyond the typical velocity offset cutoff of $\Delta v \lesssim 5000 \text{ km s}^{-1}$ used to differentiate associated absorbers from intervening systems (e.g. Foltz et al. 1986; Shen & Ménard 2012). To rule out the possibility of the absorber being associated with the AGN, we compared the apparent column density profiles of higher order Lyman series lines (see Fig. 2). The lines show similar apparent column density across the full range of the velocity of absorption, implying little partial coverage of the background AGN continuum. More generally, the high-ionization lines associated with outflows are expected to be significantly stronger and saturated than the absorption in Ne VIII, O VI or the unsaturated absorption in S V or S VI seen for this system (Fox et al. 2008; Muzahid et al. 2013). Based on the absence of any observational signatures, we conclude that the absorption is not tracing quasar-driven outflows or gas close to the AGN central engine.

The Voigt profile fitting software *VPFIT* (ver 10.0)³ was used to estimate the column density, Doppler b -parameter and the rest-frame velocity centroids of the lines. The atomic line list and oscillator strength values used for fitting are from Morton (2003) for $\lambda > 912 \text{ \AA}$ and from Verner, Verner & Ferland (1996) for $\lambda \leq 912 \text{ \AA}$. The atomic data for Ne VIII 770, 780 are $\lambda = 770.4089, 780.3240 \text{ \AA}$, and $f_{770} = 0.1030, f_{780} = 0.0505$, respectively (Verner et al. 1996). The spectral resolution of COS is known to be wavelength dependent. Therefore, while fitting, we used the empirical line spread functions developed by Kriss (2011) for the respective COS gratings. The synthetic Voigt profiles were convolved with the COS line spread function nearest in wavelength to the redshifted location of the absorption line. Profile fit results are shown in Table 2. The line profile models are shown in Fig. 1. The errors listed from the profile fit are a combination of statistical errors and continuum placement errors. The latter quantity was estimated by exploring a few different continuum fits and the resultant range of values obtained for column densities and b -values by fitting the region. Overall, we found the statistical noise in the data to be more significant than the systematic errors.

We have relied on single-component profiles to model the absorption seen in H I and the various metal lines. A few of the Lyman series lines (particularly H I 923 and H I 926) suggest multi-component structure to the core absorption in H I, albeit at low significance. The N IV 765 line also suggests possible kinematic substructure.

The apparent column density profiles of these lines are compared in Fig. 2. A free fit to the N IV line recovers three components at $v \sim -30, +6, +43 \text{ km s}^{-1}$. A similar three-component structure is not visibly evident in the unsaturated higher order Lyman lines, except H I 923 and H I 926, although there appears to be complexity to the H I velocity structure.

Taking a cue from the component structure seen in N IV, we attempted a simultaneous three-component fit to the Lyman series lines to determine the H I corresponding to the components of N IV. The fit results are given in Table 2. The column density profiles of the various Lyman series lines slightly differ from each other due to statistical fluctuations in the noise spectrum. Because of this, the multi-component profile models do not fit all the Lyman series lines equally well. The errors on column densities and b -parameters derived from the simultaneous fit reflect this. In Section 5.2.1, we discuss how the ambiguity in the component structure for H I affects the elemental abundance estimate for a warm plasma traced by the Ne VIII in this absorber.

No unique sub-component structure is evident in the unsaturated S IV 748, S V 786, S VI 933, 945 lines, and hence these lines are fitted with a single component. The comparatively strong O III, C III and O IV lines are saturated. We fit these lines also with single components. The true error in the profile fit results for such saturated lines is likely to be larger than what the fitting routine suggests.

Using the apparent optical depth (AOD) method of Savage & Sembach (1991), we estimated the total column density of the various ions by integrating over the full velocity range over which each line feature is seen. Using this method, we also derived upper limits on column densities for lines that are non-detections and lower limits for the lines that are heavily saturated. These values are also tabulated in Table 2.

The COS spectrum provides information on O II, O III, O IV and O VI. The O II is a non-detection, whereas the O III and O IV lines are strong and quite probably saturated. The similarities in the profile structure of O III and O IV suggest a possible origin in the same gas phase. Single-component Voigt profile models explain fairly well the absorption in O IV and also the doublet lines of O III, with χ^2 goodness-of-fit values close to one. However, the profile fit results for these intermediate-ionization lines are not unique. We find line saturation effects dominating the uncertainty in the profile fits. As a result, models with different combinations of N and b can explain the observed absorption in O III and O IV without compromising on the quality of the fit. We therefore adopt the integrated apparent column density lower limits of $\log N_a(\text{O III}) > 15.0$ and $\log N_a(\text{O IV}) > 15.0$ for subsequent analysis. In the case of C III also we use the $\log N_a(\text{C III}) > 14.1$, for similar reasons. The C II 903.6 line suffers from blending with O VI 1032 from an absorber at $z = 0.4176$. We use the C II 903.9 line to constrain the C II column density.

The O VI 1032 line is heavily blended with Al II 1671 absorption from the local interstellar medium. The O VI 1038 is, however, a clean feature, which we use for constraining the column density and b -parameter. A single-component fit to the O VI 1038 yields $\log N(\text{O VI}) = 14.88 \pm 0.20$ and $b(\text{O VI}) = 44 \pm 3$ that is comparable to the integrated AOD column density of $\log N(\text{O VI}) = 14.79 \pm 0.06$ to within their 1σ uncertainty range. This implies that the O VI 1038 is adequately resolved by COS. From the N and b -values measured from O VI 1038, we synthesized the O VI 1032 line profile. The synthetic profile, when superimposed on the data, reveals the extent of contamination from Galactic Al II (see the model profile in the O VI 1032 panel of Fig. 1), which is significant and difficult to correct for.

³ <http://www.ast.cam.ac.uk/~rfc/vpfit.html>

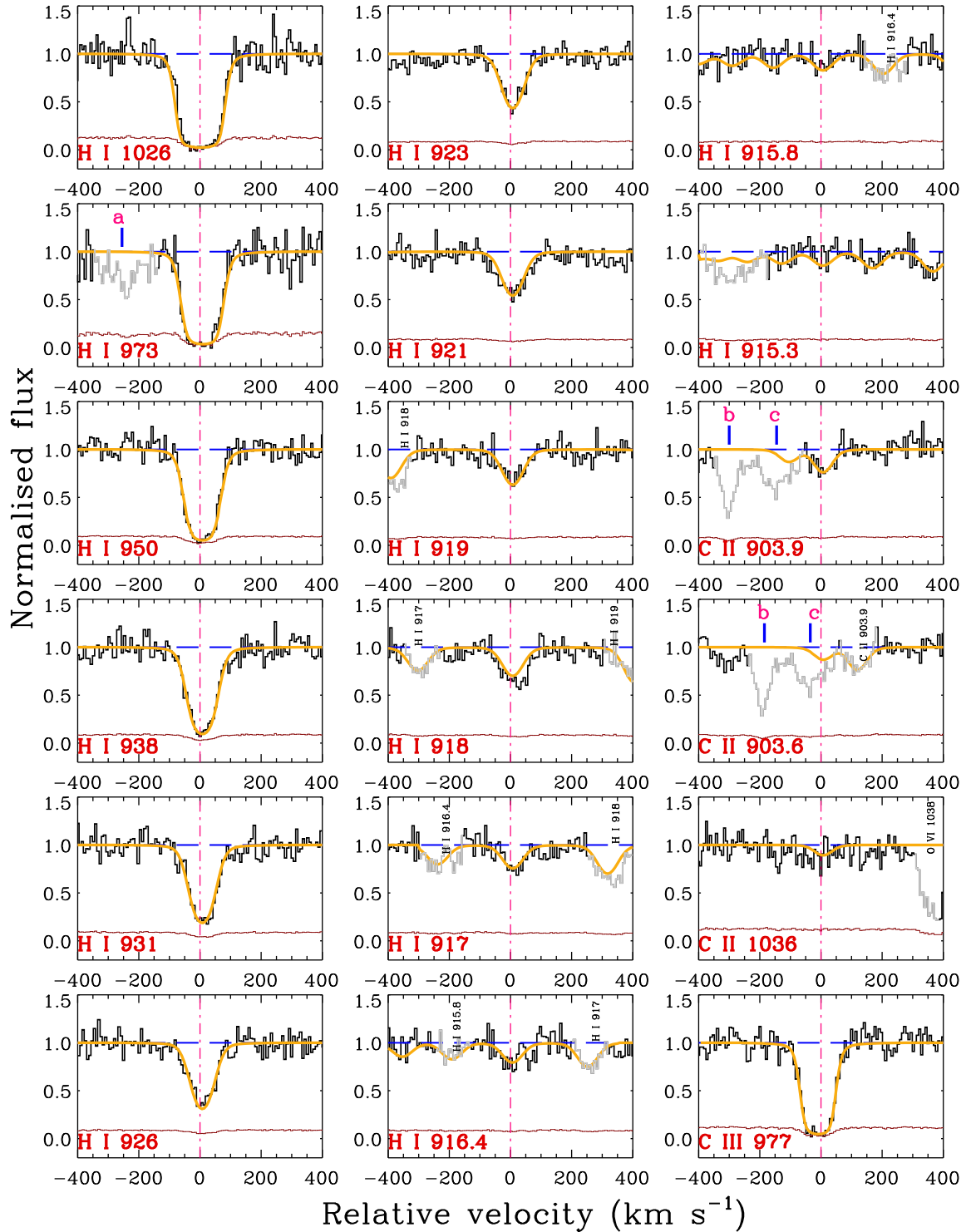


Figure 1. System plot showing the important transitions against the rest frame of the $z = 0.61907$ absorber towards the background quasar SDSS J080908.13 + 461925.6. The absorption system covers a host of Lyman series lines, metal lines such as C II, C III, N III, N IV, O III, O IV, O VI, Si IV and S V. The lines N II 916, N II 1084 and Ne VIII 780 are 3σ non-detections. C III 977 is significantly saturated. Voigt profile fits are superimposed on the respective features as yellow curves. The grey regions indicate contaminations, i.e. absorption unrelated to this particular absorber. Contaminations are identified as (a) H I 950 associated with the quasar, (b) possible Ly α from $z = 0.2027$ and (c) O VI 1032 at $z = 0.4176$ confirmed by the detection of the corresponding O VI 1038. The system plot for the $z = 0.61907$ absorber shows single-component Voigt profile fits to fairly well detected lines in the $z = 0.61907$ absorber. The centroid of the absorbing component is marked with a red vertical tick mark. The grey regions in some of the panels indicate contamination. Voigt profile fit results are shown as yellow curves, and the fit results are given in Table 2. The O III and O IV lines are significantly saturated. The O VI 1032 line is heavily blended with Galactic Al II 1671. The expected O VI 1032 absorption profile is shown in yellow in that panel, based on the uncontaminated O VI 1038 absorption. The contaminations in the various panels are (d) H I 1026 at $z = 0.5637$, for which the corresponding H I 972 is detected, (e) possibly H I 1216 at $z = 0.020$, (f) O VI 1032 at $z = 0.3076$ confirmed by the presence of the weaker O VI 1038 line, (g) Galactic Al II 1671, (h) Si II 1206 at $z = 0.0466$ for which other metal lines are also detected, (i) H I 1216 at $z = 0.0403$, (j) and (k) possibly H I 1216 at $z = 0.0465$, respectively.

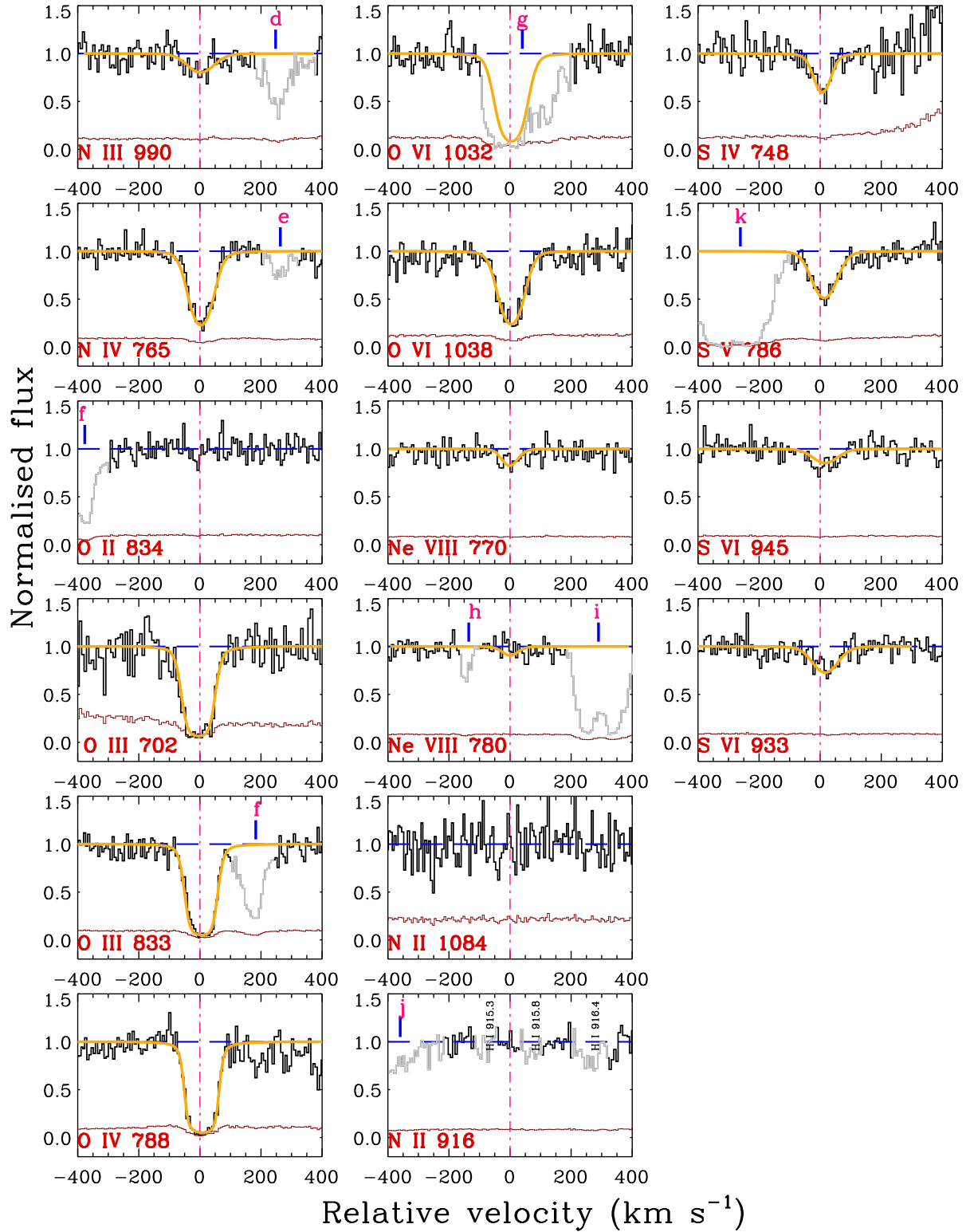


Figure 1 – continued

3.1 The Ne VIII 770, 780 detection

The Ne VIII 770, 780 is a very weak feature in the $z = 0.61907$ absorber. The ion is detected with $\gtrsim 3\sigma$ significance only in the stronger member of the doublet. The transitions fall at the blue end of the G130M grating exposures. The three G130M integrations

add to 3.1 ks of exposure time at the redshifted wavelength location of Ne VIII 770, 780 lines. The exposures were obtained with two different G130M central wavelength settings (one exposure centred at 1291 Å and two exposures at 1309 Å) that result in the dispersed light getting shifted in the detector space. This helps to reduce the detector fixed pattern noise features during co-addition.

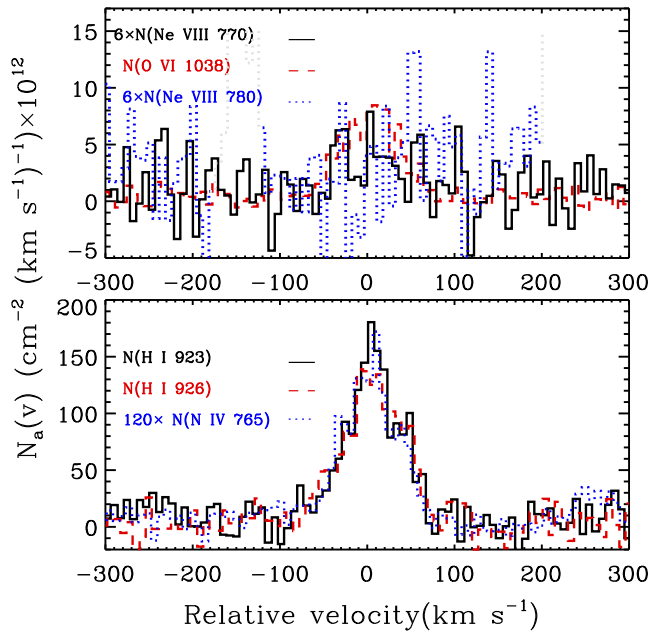


Figure 2. Top panel is a comparison of the apparent column density profiles of Ne VIII 770, 780 and O VI 1038 lines in the $z = 0.61907$ absorber. The apparent column density profile of Ne VIII 780 is truncated between $[-180, -120]$ km s $^{-1}$ and $v > 200$ km s $^{-1}$ where they suffer from contamination. The coincidence in velocity between Ne VIII 770 and O VI lends support to the detection of Ne VIII 770. In the bottom panel, the apparent column densities of two of the unsaturated Lyman series lines and N IV 765 are shown.

The Ne VIII 770 line has a rest-frame equivalent width of $W_r = 28 \pm 8$ mÅ when integrated over $[-85, 77]$ km s $^{-1}$. This is the same velocity range over which absorption from C III, O III, O IV and O VI 1038 is detected. The Ne VIII 770 feature is thus detected with a significance of 3.5σ . The uncertainty quoted for the equivalent width is inclusive of statistical and continuum placement errors. A more stringent estimate on the detection significance can be arrived at by including a systematic uncertainty of ~ 10 mÅ from residual fixed pattern noise features that could be present in COS data (Savage et al. 2014). This would bring the Ne VIII 770 significance down to 2.2σ . The non-detection of Ne VIII 780 at $\geq 3\sigma$ is consistent with the expected 2:1 equivalent width ratio between the two lines of the doublet.

The non-detection of Ne VIII 780 prompted us to investigate the validity of the Ne VIII detection in greater detail. We synthesized Ne VIII 770, 780 lines by convolving a model absorption feature (of N , and b -value obtained from fitting the Ne VIII 770) with a Gaussian kernel of FWHM = 17 km s $^{-1}$ (resolution of COS). Poisson noise was added to this synthetic profile to simulate S/N = 20 per wavelength bin (1/2 a resolution element). This approximately matches the S/N of the data in the region where the Ne VIII occurs. The result of this exercise, shown in Fig. 3, is consistent with the low significance of Ne VIII 770 and the non-detection of the Ne VIII 780 lines.

In the independent line identifications for this sightline done by Danforth et al. (2016) and one of the co-authors (Bart Wakker), the Ne VIII 770 absorption at $\lambda = 1247.35$ Å is not identified with any line associated with other absorbers along this sightline. None the less, we cannot fully eliminate the possibility of the Ne VIII 770 absorption being a weak low-redshift Ly α interloper.

We measured the strength of the Ne VIII 770 in the separate G130M integrations as well. The absorption feature is detected

with an equivalent width of $W_r = 28 \pm 11$ mÅ in the exposure with grating central wavelength of $\lambda_c = 1291$ Å, and $W_r = 51 \pm 20$ and 36 ± 20 mÅ in the two exposures with central wavelengths of $\lambda_c = 1309$ Å. The feature thus has a mean detection significance of 2.3σ in the individual science exposures.

We made a closer investigation to find out whether fixed pattern noise or similar instrumental artefacts are affecting our measurement in anyway. Since two out of the three integrations of the G130M grating were carried out with the same central wavelength and FP-SPLIT position set-up of the grating, we cannot compare the individual exposures to know whether a fixed pattern feature is occurring at the Ne VIII 770 Å redshifted wavelength of 1247.35 Å. Instead, we looked at this detector space in five other quasar observations done approximately in the same period with identical grating settings and found no evidence for any instrumental contamination.

In Fig. 2, we compare the apparent column density profiles of Ne VIII and O VI. Though the Ne VIII line is much weaker than O VI, in the approximate velocity range of $[-100, 100]$ km s $^{-1}$ the absorption seen in O VI is well matched by the absorption in Ne VIII. The similarity in the kinematics lends further support to the identification of the Ne VIII 770 line.

The detection significance of Ne VIII 770 line is lower than the significance of most of the COS Ne VIII detections reported thus far (Narayanan et al. 2009, 2011, 2012; Tripp et al. 2011; Meiring et al. 2013; Hussain et al. 2015) but is similar to the first Ne VIII detection in the IGM reported by Savage et al. (2005), where the 770 line was detected with a significance of 3.1σ . However, in the Ne VIII detection reported by Savage et al. (2005), the weaker 780 line was also a formal detection with 2.3σ significance, resulting in a higher detection significance of 3.9σ jointly for the lines of the doublet.

4 THE $z = 0.57052$ ABSORBER TOWARDS SBS 1122 + 594

The absorber is detected in H I, O IV, N IV, O VI and Ne VIII. Continuum normalized velocity plots of important transitions are shown in Fig. 4. The H I clearly shows three distinct components at -8 , -122 , -227 km s $^{-1}$. The metal lines are all aligned with the -8 km s $^{-1}$ component, which interestingly is not the strongest component in H I. The COS spectrum also covers wavelength regions where lines from C II, C III, O III, S IV and S VI are expected. The line measurements are given in Table 3. The O VI 1031, 1037 lines were simultaneously fitted freely with Voigt profiles. The lines fall in a comparatively low S/N (~ 6 per 17 km s $^{-1}$ resolution element) part of the spectrum, which is reflected in the large uncertainty associated with the fit parameters, and in the unusual equivalent width ratio between the two lines of the doublet. The doublet lines have a combined detection significance of 4.1σ . The column density from profile fitting is similar to the integrated apparent column density obtained for the 1032 and 1038 Å lines. This indicates little unresolved saturated structure in the O VI profiles. The same is also true for Ly β , N IV 765 and O IV 788 transitions. The Ly β and Ly δ lines were also simultaneously fitted with three components. The Ly γ transition was excluded from the profile fitting as the region is severely contaminated by Galactic Si II 1527 and a Ly α absorber at $z = 0.2569$. From profile fitting, we find that the H I component associated with the metal lines is fairly broad ($b \sim 50$ km s $^{-1}$). This component is undetected in Ly δ , as we expect it to be too weak. Our assumption of a simple three-component model for the H I can be a source of systematic uncertainty in the line measurements. Given

Table 2. Line measurements for the absorber at $z = 0.61907$ towards SDSS J080908.13 + 461925.6. Measurements on the various lines associated with the $z = 0.61907$ towards SDSS J080908.13 + 461925.6. The measurements were done using the apparent optical depth (AOD) and Voigt profile fitting techniques. The doublet/multiplet lines were separately and simultaneously fitted. The various columns list the rest-frame equivalent width, centroid velocity of the absorbing components, their b -parameters, column densities and the velocity ranges of integration used to estimate these parameters.

Transition	Voigt profile measurements			Total log [N (cm $^{-2}$)]
	v (km s $^{-1}$)	b (km s $^{-1}$)	log [N (cm $^{-2}$)]	
N IV 765	-30 ± 4	14 ± 4	13.47 ± 0.11	14.09 ± 0.06
(3 comp)	6 ± 2	15 ± 5	13.85 ± 0.06	
	43 ± 3	11 ± 3	13.37 ± 0.07	
N IV 765 (single comp)	3 ± 2	41 ± 2	14.05 ± 0.02	16.10 ± 0.05
H I 919–1026	-31	30 ± 9	15.50 ± 0.08	
(3 comp)	5	18 ± 9	15.82 ± 0.05	
	44	15 ± 4	15.52 ± 0.06	
H I 919–1026 (single comp)	-4	41	16.13 ± 0.02	14.88 ± 0.20
O VI 1038	4 ± 2	44 ± 3	14.88 ± 0.20	
O IV 788	6 ± 1	24 ± 4	16.53 ± 0.70^a	16.53 ± 0.70^a
O III	4 ± 2	32 ± 3	15.52 ± 0.15^a	15.52 ± 0.15^a
C III 977	-10 ± 1	33 ± 3	14.71 ± 0.20^a	14.71 ± 0.20^a
C II 903.9	8 ± 6	37 ± 9	13.42 ± 0.10	13.42 ± 0.10
S IV 748	7 ± 3	32 ± 5	13.59 ± 0.05	13.59 ± 0.05
S V 786	13 ± 3	47 ± 4	13.35 ± 0.03	13.35 ± 0.03
Ne VIII 770	11 ± 12	69 ± 20	13.96 ± 0.10	13.96 ± 0.10
C II 903.6–1036	7 ± 6	36 ± 9	13.42 ± 0.07	13.42 ± 0.07
S VI 934	17 ± 5	52 ± 7	13.49 ± 0.05	13.49 ± 0.05
N III 990	-4 ± 9	51 ± 16	13.83 ± 0.10	13.83 ± 0.10
Integrated AOD measurements				
Transition	W_r (mÅ)	log [N (cm $^{-2}$)]	$[-v, v]$ (km s $^{-1}$)	
O VI 1038	248 ± 18	14.79 ± 0.06	$[-85, +77]$	
N IV 765	182 ± 10	13.95 ± 0.05	$[-85, +77]$	
O IV 788	276 ± 11	> 15.0	$[-85, +77]$	
N III 990	58 ± 17	13.78 ± 0.15	$[-85, +77]$	
C III 977	393 ± 12	> 14.1	$[-75, 50]$	
O III 833	281 ± 10	> 15.0	$[-85, +77]$	
O III 702	267 ± 16	> 15.0	$[-85, +77]$	
C II 1036	< 63	< 13.8	$[-85, 77]$	
C II 904.9	67 ± 12	13.50 ± 0.08	$[-85, 77]$	
C II 904.6	< 140	< 14.2	$[-85, 77]$	
S IV 748	80 ± 14	13.59 ± 0.09	$[-85, +77]$	
S IV 809	46 ± 13	13.93 ± 0.12	$[-85, +77]$	
S V 786	110 ± 10	13.25 ± 0.06	$[-85, +77]$	
S VI 945	< 66	< 13.63	$[-85, +77]$	
S VI 934	60 ± 10	13.30 ± 0.08	$[-85, +77]$	
Ne VIII 770	28 ± 8	13.76 ± 0.14	$[-85, +77]$	
H I 1026	> 515	> 15.2	$[-105, 110]$	
H I 972	> 423	> 15.6	$[-105, 110]$	
H I 950	> 365	> 15.9	$[-105, 110]$	
H I 938	317 ± 12	16.00 ± 0.05	$[-105, 110]$	
H I 931	266 ± 13	16.08 ± 0.06	$[-105, 110]$	
H I 926	213 ± 13	16.08 ± 0.05	$[-105, 110]$	
H I 923	126 ± 13	16.14 ± 0.06	$[-100, 100]$	
H I 921	134 ± 14	16.13 ± 0.06	$[-100, 100]$	
H I 919	73 ± 11	15.97 ± 0.09	$[-60, 75]$	
H I 918	100 ± 13	16.25 ± 0.09	$[-60, 75]$	
H I 917	50 ± 12	16.03 ± 0.11	$[-60, 75]$	
H I 916.4	55 ± 12	16.15 ± 0.11	$[-60, 75]$	

Note. ^a Among the metal lines, C III, O III and O IV are strongly saturated. The formal errors given by the profile fitting routine, listed in the table, are too small and do not account for the uncertainty due to the saturation of the line feature. In the ionization models, we use the AOD column density measurements on these lines as lower limits.

the low S/N of data, we cannot ascertain whether the true kinematic nature of the H I is more complex. Future observations involving the near-UV channel of COS will allow coverage for Ly α associated with this system, offering valuable constraints on the velocity profile of H I.

The O IV 788 and N IV 765 lines were also fitted with single-component Voigt profiles. Fig. 4 shows the profile models for these various transitions.

At the location of S V 786, there is a very weak feature detected at 2.2σ significance. We find this feature to be inconsistent with being

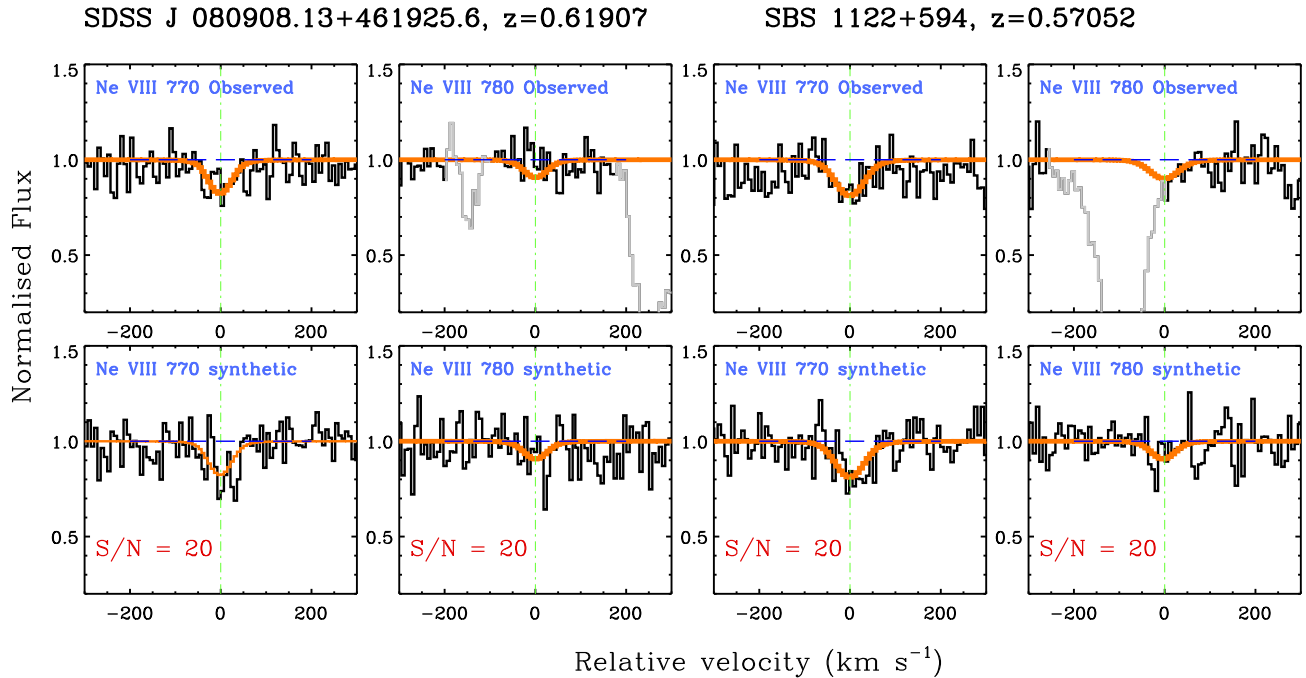


Figure 3. The top panel of the first column shows the observed Ne VIII 770 in the $z = 0.61907$ absorber, with the Voigt profile model superimposed. The bottom panel shows a synthetic Ne VIII 770 feature with identical N and b as the observed line at $S/N = 20$. The top and bottom panels of the second column show the corresponding observed and synthetic Ne VIII 780 spectra, respectively. The synthetic spectra suggest that the weak Ne VIII can be a non-detection in the 780 Å line at the S/N of the data, in agreement with observations. A similar analysis for the $z = 0.57052$ absorber is shown in panels in the third and fourth columns.

S V as none of the ionization models (discussed later) are able to simultaneously explain the detection of S V with the non-detections of its adjacent ionization stages, namely S IV and S VI. It is quite likely that this is an unidentified interloping feature.

4.1 The Ne VIII 770, 780 detection

The Ne VIII 770, 780 absorption falls at a region of the spectrum where the $S/N \sim 12$ per wavelength bin, which is a factor of 2 higher compared to the S/N at the Ly β or the O VI lines. The Ne VIII 770 feature has a rest-frame equivalent width of $W_r = 26 \pm 9$ mÅ when integrated over the velocity range from -60 to 40 km s $^{-1}$. This corresponds to a formal detection significance of 2.9σ . The statistical and the continuum placement errors have been taken into consideration in the error estimation. Including an additional 5 mÅ to account for possible detector fixed pattern residual noise features would bring the detection significance down to 2.5σ . The redshifted wavelength of the accompanying Ne VIII 780 feature is contaminated by a strong Ly β feature from an absorber at $z = 0.1944$ for which corresponding Ly α , C III, O VI and several other metal lines are seen. The contamination renders a measurement on Ne VIII 780 impossible.

In the individual exposures, the Ne VIII 770 has rest-frame equivalent widths of $W_r = 31 \pm 19$, 17 ± 20 , 24 ± 18 and 28 ± 18 mÅ for observations with G130M grating central wavelengths of 1291, 1300, 1309 and 1318 Å, respectively. All of these observations have the same FP-SPLIT position. As with the previous case, we compared the spectra of a set of five quasars with the same COS grating settings and find no evidence for fixed pattern noise in this region of detector space. The absorption reported as Ne VIII 770 occurs at $\lambda = 1209.85$ Å. This is not identified as an interloping line from other absorbers discovered along this sightline in the independent

line identifications done by Danforth et al. (2016) and one of the co-authors (Bart Wakker).

5 IONIZATION AND ABUNDANCES IN THE $z = 0.61907$ ABSORBER

To assess the density and temperature phases traced by this absorber, and the relative chemical abundances within them, we turn to time-independent photoionization-recombination equilibrium models and collisional ionization models. We first describe the results from photoionization modelling. The models were computed using the standard photoionization package CLOUDY (ver 13.03) last described by Ferland et al. (2013). CLOUDY models the absorbing gas as constant-density plane-parallel slabs irradiated by ionizing photons. The intensity and shape of the ionizing spectrum are assumed to be the EBL coming from AGNs and star-forming galaxies in the Universe. The ionizing radiation field we adopt is the upgraded model of KS15, which incorporates the most recent measurements of quasar luminosity function from Croom et al. (2009) and Palanque-Delabrouille et al. (2013), and star formation rate densities from Khaire & Srianand (2015b). A source of uncertainty in the models for EBL is the escape fraction of Lyman continuum photons from star-forming galaxies. KS15 find that an escape fraction of 4 per cent is required to match the observed IGM H I photoionization rate as measured by Kollmeier et al. (2014) and Wakker et al. (2015) and 0 per cent to match the measurements by Shull et al. (2015) and Gaikwad et al. (2017a,b). Bearing in mind this uncertainty, we computed photoionization models for both $f_{\text{esc}} = 4$ and 0 per cent, and discuss the results for both cases. For brevity, we only display the modelling predictions for the $f_{\text{esc}} = 4$ per cent case. In the models, we assume the solar relative elemental abundances given by Asplund et al. (2009).

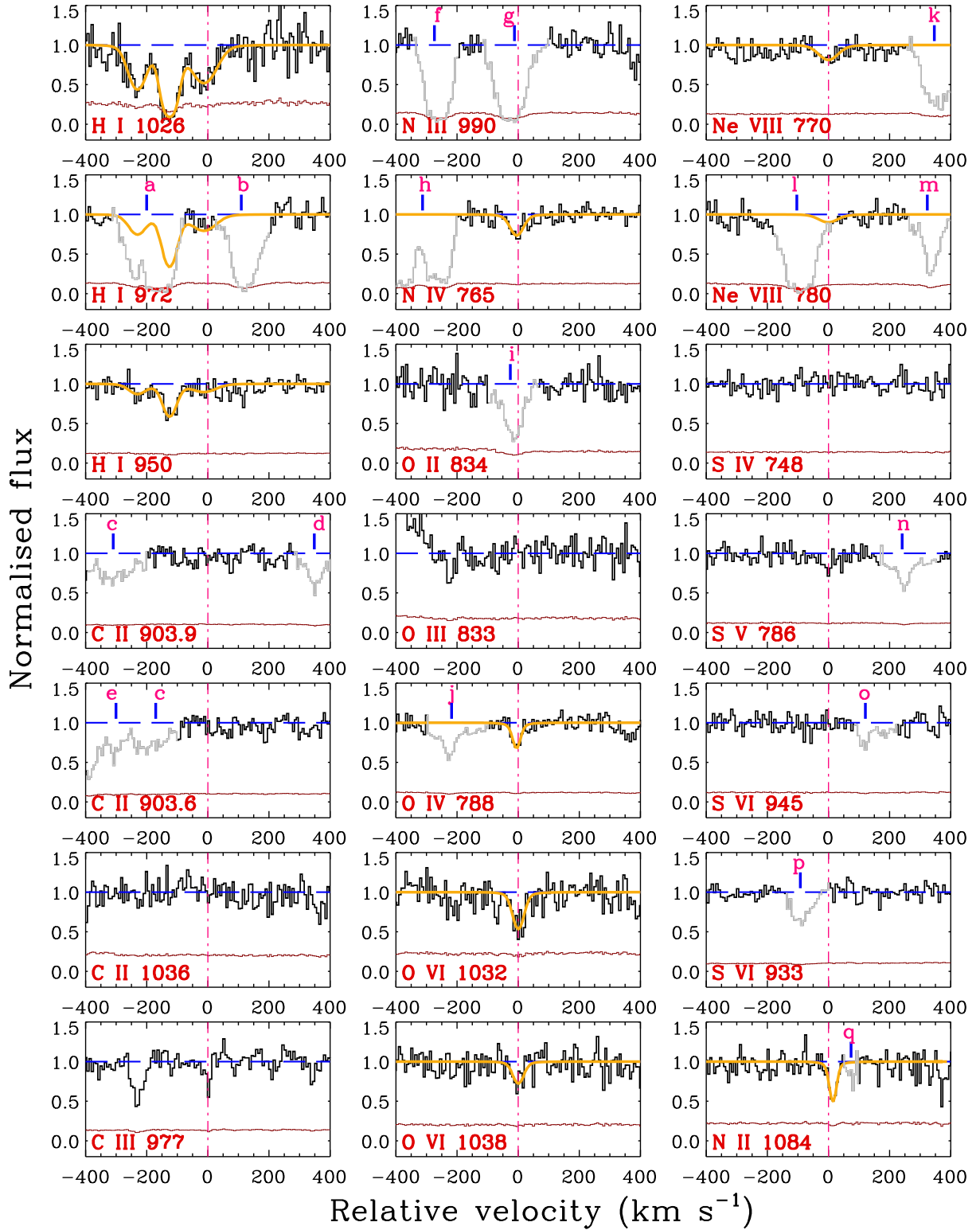


Figure 4. The continuum normalized spectra of the $z = 0.5702$ absorber towards SBS 1122 + 594. The grey regions in the various panels indicate contamination, i.e. absorption not associated with this system. Some of the major contaminations are (a) and (b) Galactic Si II 1527, (c), (d) and (e) associated Ne VIII 770, (f) Ly α at $z = 0.2777$ for which corresponding Ly β and Ly γ are identified, (g) C IV 1548 at $z = 0.0040$ for which corresponding Ly α , Si IV $\lambda\lambda$ 1394, 1403, Si III lines are present, (h) Galactic N I 1200, (i) Ly β at $z = 0.2777$ for which corresponding Ly α and Ly γ are present, (j) possibly Ly α at $z = 0.0169$, (k) Si III 1206 at $z = 0.0040$ confirmed by the presence of corresponding Ly α , C IV $\lambda\lambda$ 1548, 1550, Si IV $\lambda\lambda$ 1394, 1403 lines, (l) Ly β at $z = 0.1944$ for which other Lyman series lines, O VI 1031, 1037, are identified, (m) possibly Ly α at $z = 0.0093$, (n) possibly Ly α at $z = 0.0163$, (o) possibly Ly α at $z = 0.2207$ and (p) O VI 1032 at $z = 0.4201$ for which higher order Lyman series lines are identified.

Table 3. Line measurements for the absorber at $z = 0.57052$ towards SBS 1122 + 594. The line measurements were done using AOD and Voigt profile fitting techniques. The various columns list the rest-frame equivalent width, centroid velocity of the absorbing components, their b -parameters, column densities and the velocity range of integration used to estimate these parameters.

Transition	Voigt profile measurements		$\log [N(\text{cm}^{-2})]$
	v (km s $^{-1}$)	b (km s $^{-1}$)	
H I 950–1026	-8 ± 7	49 ± 11	14.46 ± 0.07
	-122 ± 2	26 ± 3	14.97 ± 0.04
	-227 ± 5	34 ± 7	14.44 ± 0.06
O VI 1032–1038	4 ± 5	20 ± 6	13.95 ± 0.06
O IV 788	0 ± 4	12 ± 6	13.84 ± 0.09
N IV 765	0 ± 5	25 ± 7	13.15 ± 0.07
Ne VIII 770	-2 ± 10	38 ± 8	13.92 ± 0.14
N II 1084	10 ± 2	10 ± 4	13.93 ± 0.09

Transition	Integrated AOD measurements		$[-v, v]$ (km s $^{-1}$)
	$W_r(\text{mÅ})$	$\log [N(\text{cm}^{-2})]$	
Ne VIII 770	26 ± 9	13.72 ± 0.15	$[-60, 40]$
Ne VIII 780	<22	<13.9	$[-15, 40]$
C III 977	<40	<13.0	$[-60, 50]$
O III 833	<45	<13.8	$[-60, 50]$
S VI 933	<33	<13.0	$[-60, 50]$
S VI 945	<36	<13.3	$[-60, 50]$
S IV 748	<30	<13.1	$[-60, 50]$
C II 903.9	<30	<13.0	$[-60, 50]$
C II 903.6	<30	<13.3	$[-60, 50]$
C II 1036	<60	<13.7	$[-60, 50]$
N II 1084	52 ± 17	13.75 ± 0.18	$[-40, 20]$
H I 1026	142 ± 23	14.40 ± 0.14	$[-60, 50]$
H I 972	45 ± 13	14.31 ± 0.13	$[-60, 50]$
H I 950	32 ± 13	14.47 ± 0.14	$[-60, 50]$
O VI 1032	82 ± 21	13.92 ± 0.13	$[-60, 50]$
O VI 1038	25 ± 19	<14.0	$[-60, 50]$
O IV 788	25 ± 9	13.66 ± 0.15	$[-40, 10]$
N IV 765	41 ± 10	13.16 ± 0.12	$[-60, 50]$

5.1 Photoionization equilibrium models

Fig. 5 shows the column density predictions from photoionization for the various ions at different gas densities. The models were generated for an H I column density of 16.1 dex, the value obtained from simultaneously fitting the Lyman series lines with a single component. The coverage of successive ionization stages of carbon, nitrogen, oxygen and sulphur offers useful constraints for the ionization calculations. The density is best constrained by the measured column density ratios of $\log[N(\text{N IV})/N(\text{N III})] = 0.27 \pm 0.16$, $\log[N(\text{S VI})/N(\text{S IV})] = -0.24 \pm 0.06$, $\log[N(\text{S VI})/N(\text{S V})] = 0.01 \pm 0.05$, and the lower limits $\log[N(\text{C III})/N(\text{C II})] \gtrsim 0.7$, $\log[N(\text{N III})/N(\text{N II})] \gtrsim 0.2$ and $\log[N(\text{O III})/N(\text{O II})] \gtrsim 1.9$. These ionic column density ratios are simultaneously valid for a gas density of $n_{\text{H}} = (0.4-1) \times 10^{-3} \text{ cm}^{-3}$. At the mean value of $n_{\text{H}} = 0.7 \times 10^{-3} \text{ cm}^{-3}$, the model predicts a total hydrogen column density of $N(\text{H}) = 19.5$, a gas temperature and pressure of $T = 1.5 \times 10^4 \text{ K}$ and $p/K = 10.5 \text{ cm}^{-3}$, and line-of-sight thickness of $L = 14.6 \text{ kpc}$. The photoionization predicted temperature implies that the broadening of H I and the intermediate- and low-ionization lines is due to non-thermal motion.

The single-phase photoionization model with $f_{\text{esc}} = 4$ per cent suggests a near-solar abundance for C and O. $[\text{C}/\text{H}]$ is given by the unsaturated C II column density. $[\text{C}/\text{H}]$ is $\gtrsim -0.4$ for the model

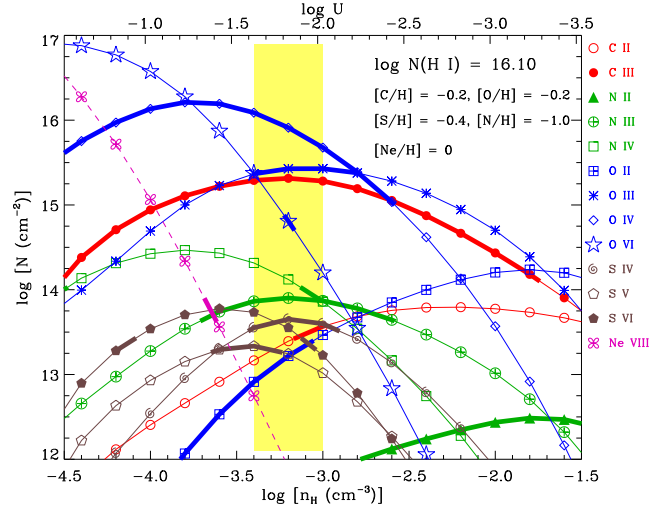


Figure 5. Photoionization equilibrium models for the absorber at $z = 0.61907$. The ionizing source is the KS15 EBR with $f_{\text{esc}} = 4$ per cent escape fraction of hydrogen ionizing photons. The thin curves show the model predicted column densities for the various ions at different densities. The thick portion in each curve is the region where the model is consistent with the observed column density to within 1σ . The predicted column density ratios of N III/N II, N IV/N III, C III/C II, S IV/S V and S/S are simultaneously consistent with observations for the narrow density range of $n_{\text{H}} \sim (0.3-1 \times 10^3) \text{ cm}^{-3}$. This region (marked in yellow) is the single-phase solution for all the ions except Ne VIII.

prediction to be consistent with the observed $N(\text{C II})$. Similarly, from the column density measurements of N III, and S IV and the lower limit on O III, we obtain abundances of $[\text{N}/\text{H}] \gtrsim -1.0$, $[\text{O}/\text{H}] \gtrsim -0.2$ and $[\text{S}/\text{H}] \gtrsim -0.4$. For these ions to be coming from the same gas phase, the abundances have to be $[\text{C}/\text{H}] = [\text{O}/\text{H}] = -0.2$, $[\text{N}/\text{H}] = -1.0$ and $[\text{S}/\text{H}] = -0.4$. The single-phase solution with these abundances is shown in Fig. 5.

The predictions from the models with an EBR of $f_{\text{esc}} = 0$ per cent are not widely different. They yield similar density for the low-ionization gas phase, with a 0.2 dex increase in the relative elemental abundances. Also at energies $>4 \text{ Ryd}$, changing the spectral shape of the EBR within the measurement uncertainty of the AGN composite continuum given by Stevans et al. (2014) would result in a ~ 0.2 dex change in the hydrogen density. The abundance estimations thus carry an approximate uncertainty of ± 0.3 dex because of the ambiguity in the escape fraction of ionizing photons, the spectral shape of the EBR and from the uncertainty in the H I column density.

This single phase with $n_{\text{H}} \sim 0.7 \times 10^{-3} \text{ cm}^{-3}$ is also consistent with the observed $N(\text{O VI})$. For $[\text{O}/\text{H}] = -0.2$ dex, the photoionized gas phase simultaneously explains the observed O VI along with its lower ionization stages. However, the predicted Ne VIII at this ionization parameter is ~ 2 dex smaller than the observed value for both versions of EBR with different f_{esc} . Producing the required amount of Ne VIII from the same gas phase would require increasing $[\text{Ne}/\text{H}]$ by a factor of 100 from its solar value. The presence of Ne VIII thus points to a separate higher ionization phase in the absorber. This separate gas phase is unlikely to be dominantly photoionized for the following reasons.

For solar $[\text{Ne}/\text{H}]$, the observed $N(\text{Ne VIII})$ is produced at ionization parameters of $\log U \geq -1.4$, corresponding to densities of $n_{\text{H}} \leq 2 \times 10^{-4} \text{ cm}^{-3}$ and for $\log N(\text{H I}) \leq 16.1$. There are two discrepancies that emerge from such a separate higher

photoionized phase. First, at $\log U \sim -3.7$, this higher ionization phase also produces significant amount of C III, N III, O III, N IV, O IV and O VI even for low values of H I. The combined column densities for these ions from the two gas phases will contradict the observed values by several factors. Secondly, the H I column density associated with this high-ionization gas is likely to be much smaller than the observed $\log N(\text{H I}) < 16.1$. To produce Ne VIII at lower values of $N(\text{H I})$ would require the line of sight to pass through very low density columns of plasma that extend over several Mpc. For example, if the H I associated with the Ne VIII gas phase has $\log N(\text{H I}) \lesssim 14$ dex, then the observed $N(\text{Ne VIII})$ will be recovered for solar $[\text{Ne}/\text{H}]$ only for $\log U \gtrsim -0.5$ corresponding to $\log n_{\text{H}} \lesssim -4.5$. The absorbing region, in this case, has to be spread over a large path-length of $\gtrsim 0.5$ Mpc, which is nearly equal to the full virial cross-section of L^* galaxies ($R_{\text{vir}} \sim 200\text{--}300$ kpc). It is unlikely for gas spread over such a large length to maintain velocity dispersions of a few tens of km s^{-1} . The other possibility is that the absorber mass has not yet decoupled from the universal expansion. In such a case, the absorption lines will suffer a velocity broadening due to Hubble expansion, which will be $v(z) = H(z)L \sim 50 \text{ km s}^{-1}$, where $L \geq 0.5$ Mpc. The observed b -value for the well-measured H I lines is 40 per cent narrower than the expected broadening due to Hubble flow.

We emphasize here that the photoionization models are not exact because of the simplistic assumptions built into them (the absorbing cloud in the models has a plane-parallel geometry with uniform density and temperature) and also due to the lack of information on the exact column densities and any sub-component structure in the saturated metal lines and H I. However, the model prediction that the Ne VIII is not consistent with photoionization is important. In the next section, we discuss the results from collisional ionization models for the Ne VIII bearing gas.

5.2 Evidence for a warm gas phase

5.2.1 Collisional ionization equilibrium models

In collisional ionization equilibrium (CIE) models, the ionization fractions of elements depend only on the equilibrium temperature. In Fig. 7, we plot the Ne VIII-to-O VI column density ratio predictions made by the CIE model of Gnat & Sternberg (2007) for a range of plasma temperatures. The CIE is a good approximation for calculating the ionization of H I, Ne VIII and O VI at $T > 2 \times 10^5$ K since the gas cools relatively slowly at such higher temperatures. For lower temperatures, non-equilibrium ionization effects (recombination lagging behind the cooling of the gas) become important (Savage et al. 2014).

The column density ratio of Ne VIII to O VI cannot be used directly to ascertain the temperature of the gas, as much of the O VI is possibly tracing the cooler photoionized medium. None the less, the presence of O VI can be used to place a lower limit on the temperature of the collisionally ionized gas. As shown in the bottom panel of Fig. 7, the ratio of $\log[N(\text{Ne VIII})/N(\text{O VI})] \gtrsim -1.25$ is valid for $T \gtrsim 4.3 \times 10^5$ K. If this warm gas phase has more Ne VIII compared to O VI, then a lower limit of $T \gtrsim 5.0 \times 10^5$ K is obtained from the CIE models. To determine the metallicity and the total hydrogen column density in this warm phase, we need an estimate on the associated H I. Even at the conservative lower limit of $T = 4.3 \times 10^5$ K, the neutral fraction of hydrogen at CIE is $f(\text{H I}) = 7.9 \times 10^{-7}$, suggesting that most of the mass in the Ne VIII gas phase is in an ionized form. Consequently, nearly all of the strong absorption in

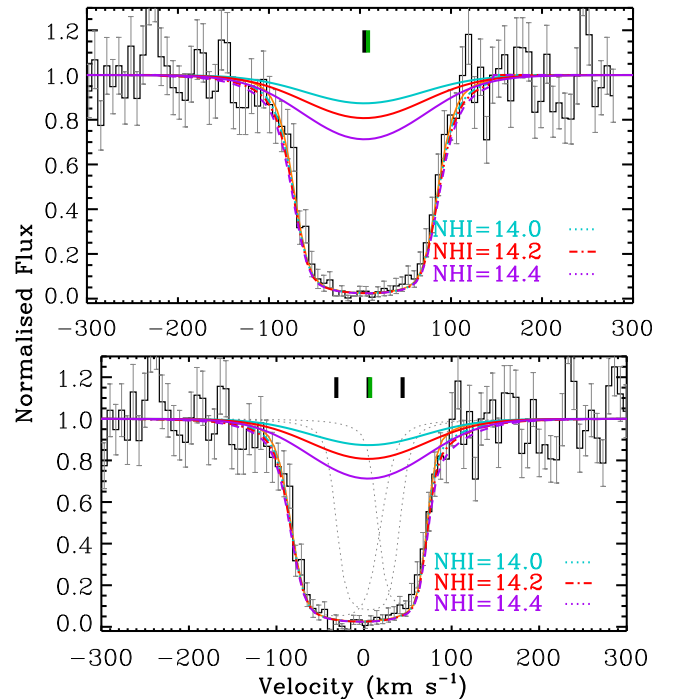


Figure 6. The figure shows the H I 1026 feature of the $z = 0.61907$ absorber towards SDSS J080908.13 + 461925.6. Superimposed on the data are different Voigt profile fits. The top and bottom panels assume a single-component ($\chi^2_v = 1.7$) and a three-component ($\chi^2_v = 1.2$) fit to the core absorption. The fit parameters are given in Table 1. To this are added broad H I profiles with a fixed $b = 85 \text{ km s}^{-1}$ and $\log N(\text{H I}) = 14.0, 14.2, 14.4$ dex centred at the velocity where Ne VIII absorption is seen (shown as solid curves of different colour). The composite of the broad and narrow H I absorptions are overlaid on the data as dashed lines. The $b = 85 \text{ km s}^{-1}$ is how broad the H I absorption from the Ne VIII gas phase would be, based on a temperature lower limit estimate for this phase. Addition of such a thermally broad and shallow H I component affects only the wings of the profile and not the core absorption. From this, we estimate an upper bound to the H I column density in the Ne VIII phase as $\log N(\text{H I}) \lesssim 14.2$ dex.

H I is potentially tracing the cooler photoionized medium. Given the low H I optical depth and the warm temperature of the gas, we expect the absorption from the residual H I to be thermally broad and shallow. The absence of coverage of Ly α makes it implausible to know whether a BLA is associated with the Ne VIII gas. At the low S/N of the data, it is difficult to search for the presence of a broad H I feature in the weaker Ly β line. We, therefore, use the Ly β to place a useful upper limit on the H I column density associated with this warm gas.

In Fig. 6 are superimposed synthetic BLA profiles on top of the Ly β absorption. The BLA profiles were synthesized for the CIE temperature lower limit of $T = 4.3 \times 10^5$ K with different H I column densities. The temperature corresponds to a pure thermal line width of $b(\text{H I}) = 85 \text{ km s}^{-1}$. We explored both single-component and three-component (refer Table 2) models for the narrow and strong absorption that forms the core of the H I profile. The three-component model is based on the weakly resolved kinematic substructure seen in the H I 923 and 926 lines, and also N IV 765. Statistically, the three components result in a better fit ($\chi^2_v = 1.2$) to the core absorption in Ly β compared to a single component ($\chi^2_v = 1.7$), although in the latter case the fitting model is within 1σ of the flux values. Irrespective of whether the core absorption is modelled by a single component or multiple components, the

thermally broad H I associated with the Ne VIII gas phase has to have $\log N(\text{H I}) \lesssim 14.2$ to go undetected in the Ly β profile. If the temperature in the Ne VIII gas phase is higher, this H I limiting column density will also be higher. The H I column density upper limit of $\log N(\text{H I}) = 14.2$ constrains the $[\text{Ne}/\text{H}] \lesssim -0.5$ in the warm gas.

Adopting $\log[N(\text{H I})] \lesssim 14.0$, CIE models predict a total hydrogen column density of $\log [N(\text{H})] \gtrsim 20.1$ for $T \gtrsim 4.3 \times 10^5$ K. This lower bound on baryonic column density is an order of magnitude more than the amount of total hydrogen present in the photoionized gas phase.

Extending the collisional ionization scenario further, we also computed models that simultaneously consider ion–electron collisions and ion–photon interactions as sources of ionization. Insights from these *hybrid* models are discussed next.

5.2.2 Hybrid of PIE and CIE

Using CLOUDY, we computed *hybrid* models that simultaneously consider PIE and CIE scenarios for different warm gas temperatures. The photoionizations are caused by the extragalactic ionizing background radiation as given by KS15. The Ne VIII-to-O VI column density ratio predicts a temperature lower limit of $T \sim 4 \times 10^5$ K from CIE. At this temperature, the hybrid models require gas densities of $n_{\text{H}} < 10^{-3} \text{ cm}^{-3}$ to be consistent with the lower bound of the Ne VIII-to-O VI column density ratio. The number density corresponds to a baryonic overdensity of $\Delta = \rho/\bar{\rho} \gtrsim 1000$ [using $n_{\text{H}}(\text{cm}^{-3}) = 1.9 \times 10^{-7}(1+z)^3\Delta$]. Simulations associate such $T - \Delta$ combinations typically with hot haloes (fig. 5 of Gaikwad et al. 2017a). For the approximate H I upper limit of $N(\text{H I}) = 10^{14.2} \text{ cm}^{-2}$ derived earlier, this gas phase model predicts $N(\text{H}) \sim 4.3 \times 10^{20} \text{ cm}^{-2}$ and an absorption path-length of $L \sim 88 \text{ kpc}$. Such a prediction is also consistent with the lower limit on Ne VIII to S VI. At that temperature and H I column density, the $[\text{Ne}/\text{H}] = -0.5$ dex to match the observed $N(\text{Ne VIII})$ at any density. Higher temperatures for the Ne VIII gas phase would predict higher density upper limits (as shown in Fig. 7). We emphasize here that given the lack of observational constraint on the amount of O VI and H I associated with the Ne VIII, the hybrid models are only as useful as the CIE models in setting limits on the physical conditions of the warm gas. Furthermore, if the true temperature of the gas is $T \lesssim 2 \times 10^5$ K, the hybrid models should assume non-CIE calculations along with photoionization for a truly valid explanation of the physical conditions. Such involved modelling is beyond the scope of this paper [but, see Oppenheimer et al. (2016) where this is attempted].

6 IONIZATION AND ABUNDANCES IN THE $z = 0.57052$ ABSORBER TOWARDS SBS 1122 + 594

The absence of low-ionization species like C II, O II, C III and O III suggests moderate- to high-ionization conditions in this absorber. Photoionization predicted column densities using CLOUDY for the various metal ions are shown in Fig. 8. The models were computed for an H I column density of 14.46 dex that we measure for the $v \sim -8 \text{ km s}^{-1}$ component. The metal ions are all coincident in velocity with this H I component. The ratio between the observed O IV and O VI is valid for a density of $n_{\text{H}} = 1.8 \times 10^{-4} \text{ cm}^{-3}$. At this density, the models are able to recover the observed column density of N IV, O IV, O VI for a metallicity of $[\text{X}/\text{H}] = -0.8$ dex. This single-phase solution, shown in Fig. 8, is also consistent with the non-detection of the low-ionization species. The single-phase

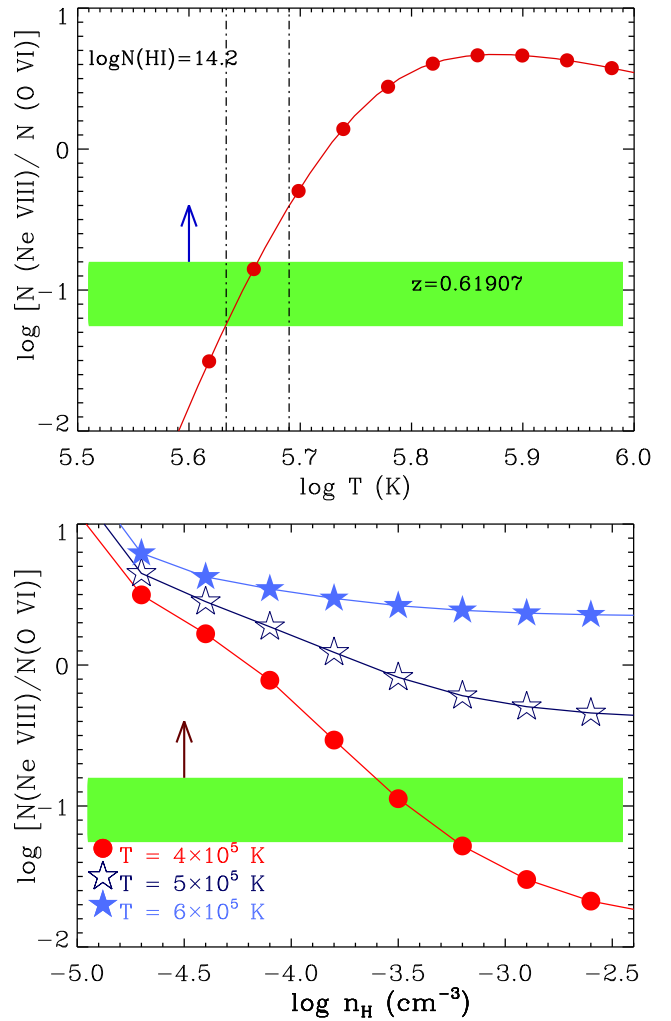


Figure 7. The top panel shows the column density ratio of Ne VIII–O VI predicted by CIE models of Gnat & Sternberg (2007) for different equilibrium temperatures and solar elemental abundance. The green shaded region is where the model predicted ratio matches with the observation for the absorber at $z = 0.61907$ towards SDSS J080908.13 + 461925.6. The upward arrow is to indicate that the observed Ne VIII–O VI column density ratio can be only considered as a lower limit on the true column density ratio between these two ions in the collisionally ionized gas phase, since O VI can have a significant contribution from the $T \sim 10^4$ K photoionized phase of this same absorber. The bottom panel shows the same ionic column density ratio predicted by photoionization–collisional ionization hybrid models for three different equilibrium temperatures of $T = 4 \times 10^5$, 5×10^5 and 6×10^5 K, respectively. The CIE models predict the Ne VIII to be from a warm gas phase with $T > 4.3 \times 10^5$ K. There is no clear constraint on the density from the hybrid models, since the Ne VIII–O VI column density ratio is only a lower limit.

model with $n_{\text{H}} = 1.8 \times 10^{-4} \text{ cm}^{-3}$ yields a total hydrogen column density of $N(\text{H}) = 18.6$, a temperature of $T = 2.7 \times 10^4$ K, a gas pressure of $p/K = 4.9 \text{ cm}^{-3} \text{ K}$ and a line-of-sight thickness of $L = 47.2 \text{ kpc}$ for the absorbing medium.

The Ne VIII column density from this gas phase is ~ 1.8 dex lower than the observed value. To explain Ne VIII from the same phase would require the $[\text{Ne}/\text{H}]$ to be ~ 10 greater than solar, whereas the C, N, O abundances are significantly sub-solar. The alternative of the Ne VIII arising in a separate photoionized phase at higher ionization parameter can also be ruled out, as such a phase will also produce significant O VI and O IV in it, which will make the

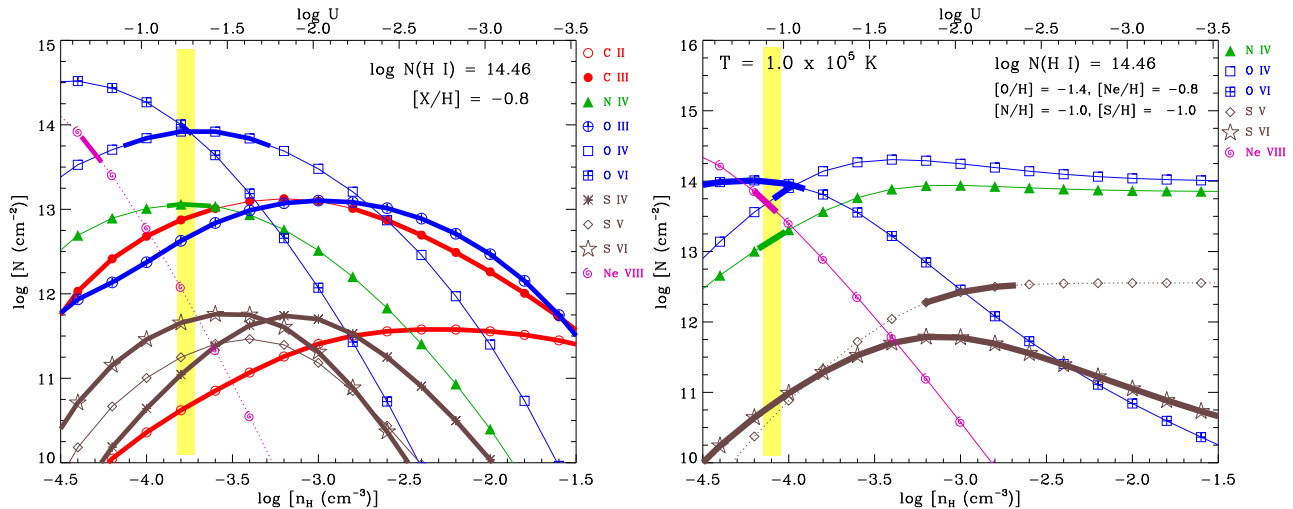


Figure 8. The left-hand panel shows the photoionization equilibrium (PIE) model for the absorber at $z = 0.57052$ with $f_{\text{esc}} = 4$ per cent in the KS15 ionizing background. The curves correspond to column density predictions at different densities for each ion, and the thick region on each curve is where the model is consistent with the observation to within 1σ . For a sub-solar metallicity of -0.8 dex and at a density of $n_{\text{H}} \sim 5 \times 10^{-3} \text{ cm}^{-3}$, the PIE model can explain the observed column density of all the ions except S V and Ne VIII. The right-hand panel shows the hybrid ionization model predictions for a temperature $T = 1 \times 10^5 \text{ K}$ and the KS15 EBR with $f_{\text{esc}} = 4$ per cent. The temperature used is based on comparing $b(\text{O VI})$ with $b(\text{H I})$. In the hybrid models, the various ions are produced from a single phase with $n_{\text{H}} \sim 10^{-4} \text{ cm}^{-3}$ for elemental abundances of $[\text{O}/\text{H}] = -1.4$, $[\text{Ne}/\text{H}] = -0.8$, $[\text{N}/\text{H}] = -1.0$ and $[\text{S}/\text{H}] = -1.0$.

two-phase solution incompatible with the observed column densities of these ions.

There is also a contradiction in the temperature arrived at through photoionization modelling and the measured b -values of H I and O VI. The different b -values for the reasonably well aligned H I and O VI suggest the temperature of this gas phase to be $T = (0.5\text{--}1.5) \times 10^5 \text{ K}$, where the range corresponds to the 1σ uncertainty in the b -values. Similar limits for temperature are obtained if we use the b -values of H I and O IV. The values are too high for UV photoionization heating. Such a conclusion rests on the assumption that the metal lines and Ly α are adequately resolved by COS. In the O IV 788, S V 786 and O VI 1032 lines, there is no immediate evidence for kinematic substructure. The N IV 765 shows slight asymmetry in the bluer side of its profile. At the given resolution and S/N, it is difficult to rule out whether the lines are narrower than what is seen by COS.

The low S/N of the data notwithstanding, the higher temperatures suggested by the line widths could mean that the collisional processes may be playing a significant role in controlling the ionization in this gas. A more realistic model for this *warm* plasma could be one where electron collisions as well as photon interactions are simultaneously considered. Such *hybrid* models are discussed in the next section.

6.0.3 Hybrid of PIE and CIE models

In Fig. 8, we have also shown the predictions from hybrid models for an EBR with $f_{\text{esc}} = 4$ per cent. The temperature of the plasma was set to $T = 10^5 \text{ K}$, which is the mean of the temperature range obtained from the thermal broadening of H I and metal absorption lines. This temperature is closer to where O VI reaches its peak ionization fraction ($T = 3 \times 10^5 \text{ K}$), compared to the peak in Ne VIII ($T = 7 \times 10^5 \text{ K}$). From the observed O IV-to-O VI ratio, the density is constrained to $n_{\text{H}} \sim 10^{-4} \text{ cm}^{-3}$, with only a slight difference between the predictions from the two flavours of EBR.

The hybrid models suggest that it is possible for N IV, O IV, O VI and Ne VIII to be coming from the same gas phase with

$n_{\text{H}} \sim 10^{-4} \text{ cm}^{-3}$, for non-solar relative elemental abundances. This gas phase model yields a total hydrogen column density of $N(\text{H}) = 4.8 \times 10^{19} \text{ cm}^{-2}$, a line-of-sight thickness of $L \sim 196 \text{ kpc}$ and represents a baryonic overdensity of $\Delta \sim 100$. The observed column densities are recovered for $[\text{O}/\text{H}] = -1.4$, $[\text{Ne}/\text{H}] = -0.8$ and $[\text{N}/\text{H}] = -1.0$. The baryonic column density and absorber size reduce to half, and the elemental abundances increase by 0.2 dex for hybrid models with $f_{\text{esc}} = 0$ per cent.

The higher-than-solar (Ne/O) ratio may appear unusual. However, the solar abundance of Ne is a poorly determined quantity. The lack of strong photospheric Ne transitions in the optical or UV is the major source of uncertainty in solar Ne abundance measurements. From X-ray spectroscopic observations of a sample of stars in the 100 pc neighbourhood of the Sun, Drake & Testa (2005) estimate a value for (Ne/O) that is 2.3 times higher than the solar value of $(\text{Ne}/\text{O}) = -0.76 \pm 0.11$ given by Asplund et al. (2009). Adopting this revised estimate for (Ne/O) with an increase of +0.3 dex will make the $[\text{Ne}/\text{H}] \sim [\text{O}/\text{H}]$ in the warm phase of the absorber.

7 GALAXIES NEAR THE ABSORBER

In this section, we discuss the galaxies that lie in the neighbourhood of the absorbers. Both sightlines are covered by the SDSS survey. The SDSS DR12 (Smee et al. 2013) spectroscopic data base is 90 per cent complete down to an r -band magnitude of $r < 17.8$ (Strauss et al. 2002). This translates into a luminosity of $\gtrsim 6L^*$ at $z \sim 0.6$ (Ilbert et al. 2005), implying that the SDSS is sampling only the very brightest galaxies at the redshifts of these absorbers.

Within a projected separation of $30 \times 30 \text{ arcmin}$ from the line of sight towards SDSS J080908.13 + 461925.6, there are seven galaxies with spectroscopic redshifts that place them within $|\Delta v| = 1000 \text{ km s}^{-1}$ rest-frame velocity of the $z = 0.61907$ absorber. Information on the galaxies is listed in Table 4, and their relative locations are shown in Fig. 10. The impact parameters of these galaxies range from 0.7 to 1.4 Mpc. The galaxy nearest to the absorber, though close-by in velocity ($|\Delta v| = 152.9 \text{ km s}^{-1}$), is at a projected separation of 1.91 Mpc. The halo radius of this galaxy

Table 4. Galaxies associated with the absorbers. Information on the galaxies identified by SDSS within $\pm 1000 \text{ km s}^{-1}$ and $30 \times 30 \text{ arcmin}^2$ from the two absorbers is listed here. The equatorial coordinates of the galaxies are in the first two columns. The third column lists the spectroscopic redshifts of the galaxies as given by SDSS. The line-of-sight velocity separation between the absorber and the galaxy is in the fourth column. The angular separation between the absorber and the galaxy in the plane of the sky, and the corresponding projected physical separation are given in the next two columns. The projected separation was estimated assuming a Λ cold dark matter Universe with $H_0 = 69.6 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.286$ and $\Omega_\Lambda = 0.714$. The apparent magnitude in the g band is given in column 7. The absolute magnitude listed in column 8 was K -corrected using the empirical K -correction given by Westra et al. (2010). The last column provides the luminosity in terms of the Schechter luminosity of $M_* = -21.06$ at $z = 0.6$ obtained from Ilbert et al. (2005). For estimating the projected separation and luminosity distance to these galaxies, we have used the cosmology calculator of Wright (2006). One of the galaxies (labelled p) has only photometric redshift available.

RA	Dec.	z	$\Delta v \text{ (km s}^{-1}\text{)}$	$\eta \text{ (arcmin)}$	$\rho \text{ (Mpc)}$	$g \text{ (mag)}$	$r \text{ (mag)}$	M_g	$(L/L^*)_g$
$z_{\text{abs}} = 0.61907 \text{ (} v = 0 \text{ km s}^{-1}\text{) Absorber towards SDSS J080908.13 + 461925.6}$									
122.360	46.3802	0.6199 ± 0.0002	153 ± 40	4.628 68	1.9	24.4 ± 0.9	21.0 ± 0.1	-18.9	0.1
122.346	46.4186	0.6207 ± 0.0002	301 ± 40	6.250 86	2.6	22.0 ± 0.1	21.2 ± 0.1	-22.0	2.3
122.662	46.2525	0.6212 ± 0.0002	385 ± 40	16.2716	6.7	23.7 ± 0.7	21.7 ± 0.2	-21.8	1.9
122.060	46.1669	0.6223 ± 0.0002	590 ± 40	13.2152	5.5	23.0 ± 0.4	20.7 ± 0.1	-21.4	3.6
122.369	46.4542	0.6215 ± 0.0003	449 ± 55	8.584 69	3.5	22.7 ± 0.3	20.9 ± 0.2	-22.7	4.3
121.689	46.4168	0.6157 ± 0.0001	-620 ± 30	25.2369	10.4	20.7 ± 0.1	20.1 ± 0.1	-22.8	5.1
122.839	46.0672	0.6239 ± 0.0002	897 ± 40	27.7513	11.4	23.4 ± 0.4	21.7 ± 0.2	-21.9	2.1
122.746	46.4922	0.61 ± 0.04^p		21.6522	8.9	23.0 ± 0.2	21.2 ± 0.1	-22.3	3.3
$z_{\text{abs}} = 0.57052 \text{ (} v = 0 \text{ km s}^{-1}\text{) Absorber towards SBS 1122 + 594}$									
171.458 83	59.169 975	0.570542 ± 0.00014	8 ± 30	0.497 249	0.197	22.3 ± 0.2	20.9 ± 0.1	-22.2	2.6
171.503 48	58.946 364	0.568724 ± 0.00017	-339 ± 50	13.613 460	5.395	22.8 ± 0.3	21.0 ± 0.1	-22.1	3.0
171.628 53	58.931 547	0.569372 ± 0.00050	-215 ± 100	15.236 410	6.039	22.2 ± 0.2	20.6 ± 0.1	-22.6	4.0
170.937 17	59.008 323	0.570136 ± 0.00020	-69 ± 70	19.265 253	7.635	22.1 ± 0.1	20.8 ± 0.1	-22.3	3.2
171.707 15	58.785 227	0.573197 ± 0.00019	514 ± 70	24.341 730	9.648	21.2 ± 0.1	20.1 ± 0.1	-22.9	5.4
171.844 78	58.847 470	0.570971 ± 0.00018	90 ± 50	22.627 742	8.968	22.3 ± 0.2	20.7 ± 0.1	-22.4	3.4

can be estimated from its scaling relationship with luminosity given by Stocke et al. (2014),

$$\log R_{\text{vir}} = 2.257 + 0.318C + 0.018C^2 - 0.005C^3, \quad (1)$$

where $C = \log(L/L^*)$. The estimated luminosity of $0.1L^*$ suggests a halo radius as $R_{\text{vir}} = 91 \text{ kpc}$, which is 20 times smaller than the projected separation in the plane of the sky between the absorber and the galaxy. Given this large separation, the Ne VIII–O VI absorber is unlikely to be coming from gas embedded within the hot halo of the galaxy. We cannot rule out the possibility of the absorber being associated with a $\leq L^*$ galaxy (or even brighter) closer to the sightline, but undetected by SDSS. Indeed, galaxies close-by in velocity and physical separation to Ne VIII absorbers are known to span a wide range in luminosities from sub- L^* to $>L^*$ (Chen & Mulchaey 2009; Mulchaey & Chen 2009; Tripp et al. 2011; Meiring et al. 2013).

The seven galaxies that are coincident in redshift with the absorber have a narrow velocity dispersion of $\sigma \sim 85 \text{ km s}^{-1}$ and an average systemic velocity of $\sim 485 \pm 16 \text{ km s}^{-1}$ with reference to the absorber redshift. The abundance of $\gtrsim L^*$ galaxies within such a narrow range of projected physical separation and velocity offset indicates that the line of sight is possibly passing through a group medium. Given the limited number count of galaxies at the redshift of the absorber and the incompleteness of the sample for even L^* luminosities, it is not realistic to formally define a galaxy group through a friends-of-friends approach, or similar standard algorithms.

We used random sampling to investigate whether the line of sight is indeed probing an overdensity region, or if the detection of galaxies is consistent with their random distribution in space. We selected 100 different locations within the SDSS footprint at random

and searched for galaxies at $z = 0.6$ that lie within $30 \times 30 \text{ arcmin}$ and $|\Delta v| = 1000 \text{ km s}^{-1}$ of each location. The frequency distribution from this random sampling, shown in Fig. 9, suggests that there is only a 15 per cent chance of finding more than six galaxies within the sampled volume. During more than half the number of times (~ 56 per cent), our sampling found only two galaxies or less in the search window, indicating that the region intercepted by SDSS J080908.13 + 461925.6 at the location of the absorber is most likely an overdensity region, such as a group or cluster environment.

The $z = 0.57052$ absorber towards SBS 1122 + 594 also resides in a galaxy overdensity region with six galaxies identified within $|\Delta v| = 1000 \text{ km s}^{-1}$ of the absorber. The distribution of galaxies is shown in Fig. 10 with open circles, and their information is listed in Table 4. The nearest galaxy with a spectroscopically confirmed redshift is nearly at the systemic velocity of the absorber, at a close-by projected separation of $\rho = 197 \text{ kpc}$. The $L = 2.6L^*$ luminosity of the galaxy suggests that the absorber is residing well within the galaxy's virial radius of $R_{\text{vir}} = 245 \text{ kpc}$. The impact parameter is also comparable to the size of O VI absorbing haloes around luminous galaxies at low z (Tumlinson et al. 2011; Werk et al. 2013; Muzahid 2014). The second closest galaxy to the absorber is at a projected distance of $\sim 5 \text{ Mpc}$ and displaced in velocity by $|\Delta v| \sim 339 \text{ km s}^{-1}$. The average systemic velocity of the galaxies relative to the absorber is $-27 \pm 26 \text{ km s}^{-1}$ and the velocity dispersion is 111 km s^{-1} .

The densities predicted by the hybrid models correspond to overdensities ($\Delta = \rho/\bar{\rho} \gtrsim 10^2$) that are reminiscent of hot haloes and the warm-hot intergalactic gas in simulations (Smith et al. 2011; Gaikwad et al. 2017a). The $z = 0.57052$ absorber is well within the virial radius of a $2.6L^*$ galaxy. Using the r -band magnitude and halo mass (M_h) relationship given by Tinker & Conroy (2009), we

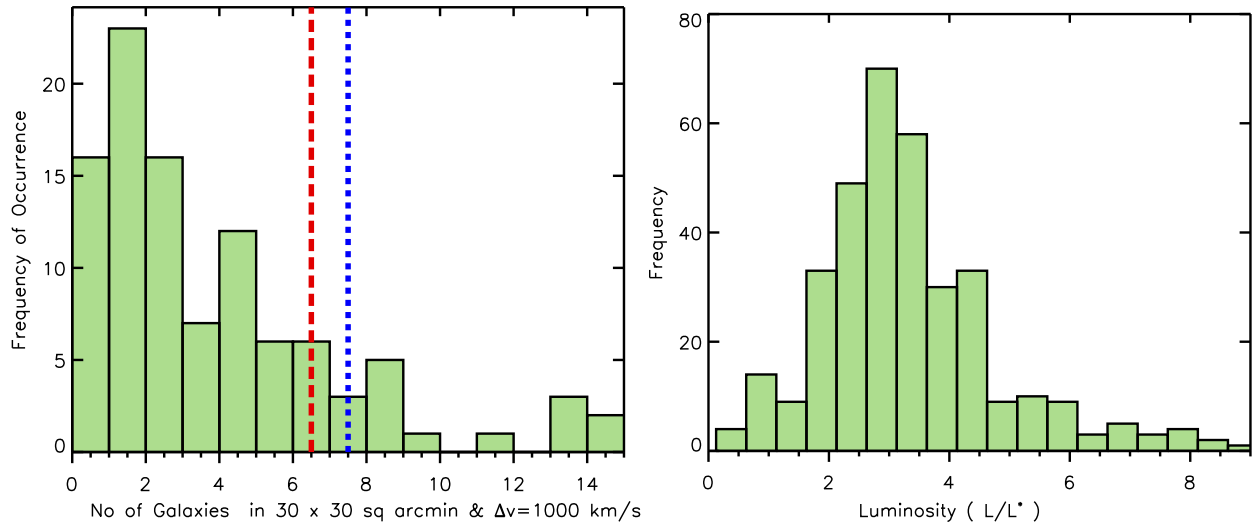


Figure 9. The left-hand panel shows the distribution of galaxies within 30×30 arcmin and $|\Delta v| = 1000$ km s $^{-1}$ of $z = 0.6$ in 100 locations randomly sampled from the SDSS footprint. The distribution indicates that there is only a small (15 per cent) probability of finding more than six galaxies in the sampled volume. More than half the number of times (~ 56 per cent) one finds only two galaxies or less in the chosen search window, implying that the galaxy overdensity seen near to both Ne VIII absorbers is not random coincidence. The dashed and dotted vertical lines indicate the number of galaxies found in the same region of space around the $z = 0.57052$ and 0.61907 Ne VIII absorbers. The right-hand panel shows the luminosity distribution of the galaxies from the random sampling, indicating that the completeness of SDSS is poor for $L \lesssim 3L^*$ at $z = 0.6$, which is in turn consistent with the large luminosities that we find for the galaxies in the extended environment around both Ne VIII absorbers.

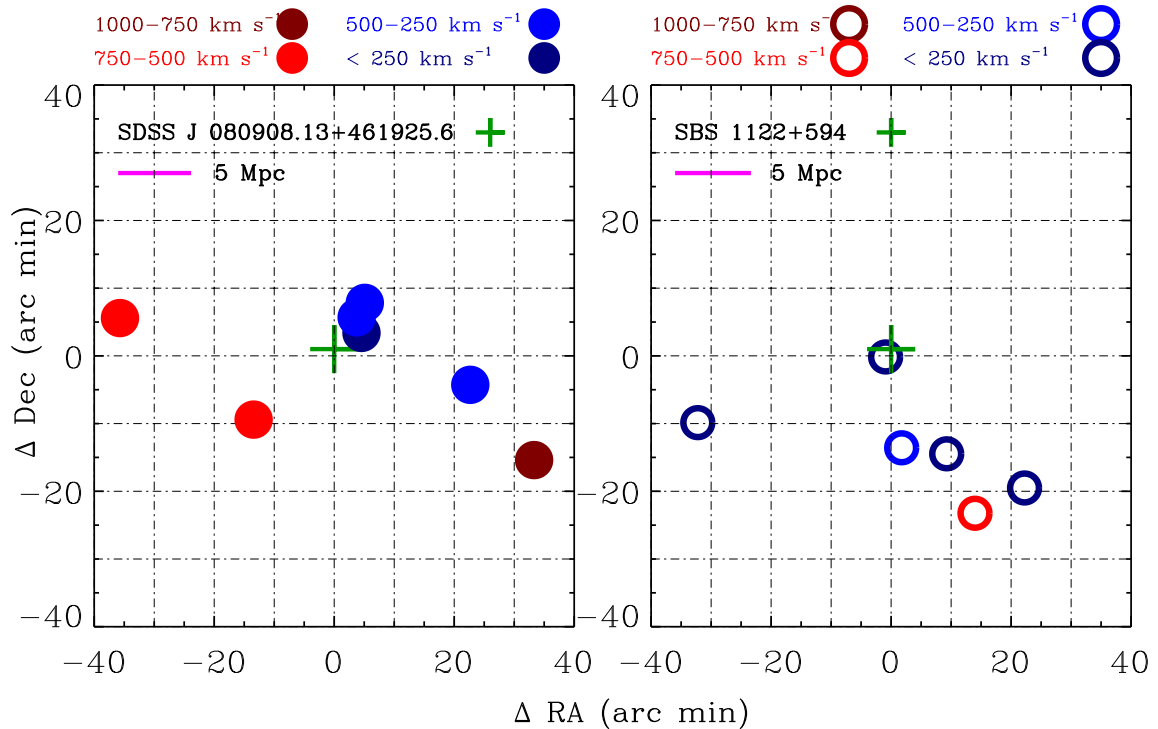


Figure 10. Figure shows the galaxies observed in SDSS survey within 30×30 arcmin and 1000 km s $^{-1}$ from the absorbers detected at $z = 0.61907$ (left-hand panel) and $z = 0.57052$ (right-hand panel) towards the QSO sightlines SDSS J080908.13 + 461925.6 and SBS 1122 + 594, respectively. Galaxies associated with $z = 0.61907$ absorber are shown with filled circles and those associated with $z = 0.57052$ are shown with open circles where the colour coding corresponds to the velocity separation of the galaxy from the absorber. The line of sight is indicated by the ‘+’ sign.

estimate that this galaxy resides in a halo of minimum mass $M_h \sim 10^{14} M_\odot$. The corresponding virial temperature of the dark matter halo comes out to be $T_{\text{vir}} \sim 10^7$ K. Since the halo mass is greater than the critical mass of $M_h \sim 10^{11} M_\odot$ for virial shocks (Birnboim & Dekel 2003), any gas accreted by the galaxy from the

surrounding will be initially shock heated to the halo virial temperature. Subsequently, the gas can radiatively cool falling out of hydrostatic equilibrium with the halo. With our estimates of $T \sim 10^5$ K, $n_H \sim 10^{-4}$ cm $^{-3}$ and $[X/H] \sim -1.0$, the instantaneous radiative cooling time-scale comes out as $t_{\text{cool}} \sim 20$ Myr (Sutherland

& Dopita 1993). These estimates hint at the possibility that the $z = 0.57052$ absorber, with its comparatively low metallicity, could be material infalling into the hot extended corona of the galaxy.

In the case of the $z = 0.61907$ absorber, the SDSS data only suggest that the Ne VIII is in a high-density region of luminous, massive galaxies. This general picture is consistent with more exhaustive absorber-galaxy surveys that have repeatedly found warm absorbers closely associated with galaxy overdensity regions (e.g. Chen & Mulchaey 2009; Wakker & Savage 2009; Narayanan et al. 2010b; Stocke et al. 2014; Werk et al. 2016). Only by extending the galaxy completeness to fainter magnitudes will it be possible to say whether the Ne VIII is coincidental with the warm extended envelope of an L^* or fainter galaxy or the shock-heated gas in intergalactic filaments.

8 SUMMARY AND CONCLUSIONS

We report on the detection of two intervening Ne VIII absorbers at $z = 0.61907$ and 0.57052 in the *HST*/COS far-UV spectrum of the background quasars SDSS J080908.13 + 461925.6 and SBS 1122 + 594, respectively. The key results are the following.

(i) The $z = 0.61907$ absorber is seen in H I, C II, C III, N III, O III, N IV, O IV, O VI and Ne VIII. The Ne VIII 770 line is detected with a significance of 3.0σ taking into account the statistical and systematic uncertainties. The total column density of the ion is estimated to be $\log[N(\text{Ne VIII}), \text{cm}^{-2}] = 13.76 \pm 0.14$. The Ne VIII 780 line is a non-detection.

(ii) Ionization models suggest a two-phase solution for the $z = 0.61907$ absorber. The low and intermediate ions are most consistent with photoionized gas with $n_{\text{H}} \sim 7 \times 10^{-4} \text{ cm}^{-3}$, $T \sim 1.5 \times 10^4 \text{ K}$, $p/K \sim 10.5 \text{ cm}^{-3} \text{ K}$ and an absorption path-length of $L \sim 14.6 \text{ kpc}$. The ionic column densities yield abundances of $[C/H] = [O/H] = -0.2$, $[N/H] = -1.0$ and $[S/H] = -0.4$, with an uncertainty of ± 0.3 dex. The O VI is also consistent with an origin in this photoionized gas phase.

(iii) The Ne VIII in the $z = 0.61907$ absorber is found to be tracing a higher temperature gas phase that is dominantly collisionally ionized. The observed $\log[N(\text{Ne VIII})/N(\text{O VI})] \gtrsim -1.25$ indicates CIE temperatures of $T \gtrsim 4.3 \times 10^5 \text{ K}$ for this phase. Using hybrid models of photoionization and collisional ionization, we find this warm phase of the gas to be at $n_{\text{H}} \leq 10^{-3} \text{ cm}^{-3}$, corresponding to an overdensity of $\Delta \sim 1000$. The H I absorption associated with this gas phase is unknown. Hence, the total hydrogen column density, absorber line-of-sight thickness and neon abundance are only approximately constrained to $N(\text{H}) \sim 2.7 \times 10^{20} \text{ cm}^{-2}$, $L \sim 87 \text{ kpc}$ and $[\text{Ne}/\text{H}] \sim -0.5$.

(iv) The $z = 0.57052$ absorber has H I, N IV, O VI and Ne VIII detected. The Ne VIII 770 line has a significance of 2.9σ . The b -parameters for O VI and the corresponding H I component indicate temperature in the range of $T = (0.5\text{--}1.5) \times 10^5 \text{ K}$, which is also consistent with the line widths of O IV and N IV, and supports collisional ionization.

(v) At those warm temperatures, the hybrid models offer a single-phase solution with $n_{\text{H}} \sim 10^{-4} \text{ cm}^{-3}$ for all the detected ions, corresponding to overdensities of $\Delta \sim 100$. This warm gas phase has a total hydrogen column density of $N(\text{H}) = 4.8 \times 10^{19} \text{ cm}^{-2}$ and a thickness of $L \sim 196 \text{ kpc}$, with $[\text{Ne}/\text{H}] \sim [\text{O}/\text{H}] \sim -1$ dex.

(vi) Both warm absorbers are tracing regions where there are a number of galaxies. Over a uniform projected physical separation of $\sim 10 \text{ Mpc}$ and a velocity separation of $\Delta v \sim 1000 \text{ km s}^{-1}$, seven galaxies are identified by SDSS near to the $z = 0.61907$ absorber,

and six galaxies around the $z = 0.57052$ absorber. In the latter case, the absorber is within the halo virial radius of a $2.6L^*$ galaxy and could be tracing a shock-heated gas cloud in the circumgalactic halo of the galaxy.

Recently, Hussain et al. (2017) remodelled 7 out of the 10 previously known Ne VIII absorbers by replacing the earlier UV background models of Haardt & Madau (1996, 2012) with the KS15. The KS15 radiation field, with the recently updated QSO emissivities and Spectral Energy Distributions, has a ~ 3 times higher intensity compared to Haardt & Madau (1996, 2012) at energies $>4 \text{ Ryd}$ where the ionization potentials of O VI and Ne VIII lie. They found that in the absence of any direct evidence for warm-hot temperatures (i.e. the detection of a thermally broad Lyman α line), the Ne VIII can also be explained through photoionization. The KS15 background yields an order of magnitude higher values for density and metallicity compared to the Haardt & Madau (1996). This results in the absorber line-of-sight thickness decreasing from an unrealistically large $\gtrsim \text{Mpc}$ scale to $10\text{--}200 \text{ kpc}$, thereby making the photoionization solution a viable alternative. In the same models, the photoionized Ne VIII gas requires solar, and in most cases supersolar (nearly 10 times solar) metallicities to match the observed metal line column densities (Hussain et al. 2017). This is suggestive of the absorption tracing gas that is directly enriched by star formation, and not the canonical low-metallicity Warm - Hot Intergalactic Medium distant from galaxies that simulations predict. On the other hand, the sample of absorbers discussed in this paper have sub-solar metallicities. Interestingly, in the $z = 0.57052$ system for which we have an ionization model-independent measure on the warm temperature, the $[\text{Ne}/\text{H}] \sim -1.0$ dex, in agreement with the general predictions of Hussain et al. (2017) that at low metallicities, Ne VIII can stay longer at high temperature.

Through cosmological simulations, Tepper-García et al. (2013) had investigated the physical origin of Ne VIII systems. Their analysis demonstrates that the peak ionization fraction of $f(\text{Ne VIII}) \sim 10$ per cent is achieved through photoionization only at very low densities of $n_{\text{H}} \sim 10^{-6} \text{ cm}^{-3}$ (with the KS15 background this changes to 10^{-5} cm^{-3}) and $T \sim 10^4 \text{ K}$ in contrast to collisional ionization ($n_{\text{H}} \sim 10^{-4} \text{ cm}^{-3}$, $T \gtrsim 10^5 \text{ K}$). As a result, for the same metallicity, the $N(\text{Ne VIII}) \propto (n_{\text{H}}T)^{1/2}$ comes out as $\sim 1\text{--}2$ orders of magnitude more when it is tracing a warm (collisionally ionized) phase compared to a photoionized case. Observationally, collisionally ionized Ne VIII will therefore be easier to locate in spectra of adequately high sensitivity. Considering this, it is possible that most of the Ne VIII detections reported till now (Table 1) are likely to be tracers of warm plasma and to a lesser extent photoionized gas. It needs to be mentioned here that the results of Tepper-García et al. (2013) differ from the simulations of Oppenheimer et al. (2012) who find Ne VIII to be predominantly from $T \sim 10^4 \text{ K}$ phase of the low- z IGM. The simulations are inconclusive because of the differences between them in the treatment of physics, the assumptions made and in the implementation of Galactic-scale processes. Given such circumstances, the interpretation of observations based on simulations should be done with prudence.

In certain cases, the data cooperate in a way that allows one to infer the thermal conditions in the absorber without depending on ionization models. For example, in the Ne VIII absorbers reported by Savage et al. (2005, 2011) and Narayanan et al. (2009, 2012), the presence of a BLA (albeit at low significance) offered a direct measure on the temperature ($T \sim 5 \times 10^5 \text{ K}$) of the Ne VIII phase of the gas. Similarly, for the $z = 0.57052$ absorber in this paper, the temperature of the warm plasma was ascertained from the different

b -values of the metal lines and H I. Identifying BLAs in metal line systems traced by O VI and Ne VIII is possibly one of the best ways to infer the presence of warm-hot gas. Detection of thermally broad and shallow H I components in an unambiguous way, particularly in multiphase absorbers, will depend on the availability of high (S/N $\gtrsim 50$) spectroscopic observations with *HST*/COS.

ACKNOWLEDGEMENTS

This work is based on observations with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 05-26555. This work is based on the data obtained from the Mikulski Archive for Space Telescopes (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. SP and AN thank the Department of Space, Government of India, and the Indian Institute of Space Science and Technology for financial support for this work. SM acknowledges support from European Research Council (ERC), Grant Agreement 278594-GasAroundGalaxies.

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