COSMIC ORIGINS SPECTROGRAPH DETECTION OF Ne viii TRACING WARM–HOT GAS TOWARD PKS 0405–123*

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ABSTRACT

We report on the detection of Ne viii in the Hubble Space Telescope/Cosmic Origins Spectrograph (COS) spectrum of the intervening absorption system at z = 0.495096 toward PKS 0405–123 (zem = 0.5726). The high signal-to-noise COS spectrum also covers absorption from H I, C iii, O iii, O iv, and O vi associated with this multiphase system. The Ne viii is detected with high significance in both lines of the doublet, with integrated column densities of log Nα(neii 770) = 13.96 ± 0.06 and log Nα(neii 780) = 14.08 ± 0.07. We find the origin of Ne viii consistent with collisionally ionized gas at T ∼ 5 × 105 K with a large baryonic column density of N(H) ∼ 1019–1020 cm−2. The metallicity in the Ne viii gas phase is estimated to be [Ne/H] ∼ −0.6 ± 0.3 dex. The intermediate ions such as C iii, O iii, O iv, and H I are consistent with photoionization in lower ionization gas at T ∼ 104 K. The O iv in this absorber can have contributions from both the photoionized and collisionally ionized gas phases. The absorber is at |Δv| = 180 km s−1 systematic velocity and ρ = 110 h−1 kpc projected separation from an MR = −19.6 galaxy of extended morphology. The collisionally ionized gas at T ∼ 5 × 105 K detected in Ne viii and O vi points to an origin in multiphase gas embedded in the hot halo of the galaxy, or in nearby WHIM structure. The high-sensitivity UV spectroscopy afforded by COS has opened up new opportunities for discovering large reservoirs of missing baryons in the low-z universe through the detection of Ne viii systems.

Key words: galaxies: halos – intergalactic medium – quasars: absorption lines – quasars: individual (PKS 0405–123) – ultraviolet: general

Online-only material: color figures

1. INTRODUCTION

Absorption-line spectroscopy of distant quasars have yielded a complete census of the properties and distribution of baryons at the early epochs of the universe. At z ≥ 3, almost all of the baryons reside in the space in-between galaxies and galaxy clusters. This intergalactic medium (IGM) at high z is almost entirely in the form of gas photoionized and heated to T ∼ 106 K (e.g., Fukugita et al. 1998). The photoionized IGM manifests in the spectra of quasars as the Lyα forest. From those early epochs, the process of galaxy formation as well as the continued expansion of the universe is expected to have drastically altered the phase composition of much of the baryons (Cen & Ostriker 1999; Davé et al. 2001; Cen & Ostriker 2006). Observational efforts to detect these baryons in the present universe have so far not succeeded in identifying their most dominant reservoirs (Bregman 2007).

In the z ∼ 0 universe, collapsed objects such as galaxies, groups, and clusters account for only ≤10% of the cosmic baryon budget (Fukugita & Peebles 2004). More than 90% of the baryons are still outside of galaxies. However, unlike high-z, the fraction of intergalactic baryons in the photoionized phase far from galaxies has significantly declined. Observationally, this is evident from the decline in the redshift distribution of Lyα absorbers (Kim et al. 1997; Weymann et al. 1998; Penton et al. 2000). Estimates suggest that in the present universe, the Lyα forest contribution to the baryon density (Ωb,lyα) is only ≥30% (Penton et al. 2000, 2004; Lehner et al. 2007; Danforth & Shull 2008). This implies that a larger fraction of the intergalactic baryons must exist in a separate gas phase, not included in galaxies and also not dominantly photoionized. Numerical simulations of structure formation predict that most of these baryons are in highly ionized gas structures at temperatures in the range T ∼ 105–107 K and densities of nH ∼ (0.1–10) × 10−3 cm−3 (Cen & Ostriker 1999, 2006; Davé et al. 2001; Valageas et al. 2002). Frequently referred to as the Warm–Hot Intergalactic Medium (WHIM), this gas phase was an outcome of collisional ionization through heating in gravitational shocks when intergalactic matter fell into the potential wells of collapsed dark matter as structures grew hierarchically (e.g., Cen & Ostriker 1999). Detecting the WHIM and characterizing its physical properties remains one of the most important themes in observational cosmology. For extensive reviews on the search for WHIM in the low-z universe see Bregman (2007) and Prochaska & Tumlinson (2009).

UV absorption-line spectroscopy is presently the most promising approach for the detection and characterization of the WHIM. The diffuse nature predicted for the WHIM gas makes detection via emission scarcely possible. Also, attempts at observing the T ∼ 106 K WHIM in X-ray absorption at z > 0
have not been successful largely due to the insufficient sensitivity and resolution of the current generation of instruments. In the UV, the principal absorption-line tracers of collisionally ionized gas are \( \text{O} \, \text{vi} \lambda 1032, 1038, \text{Ne} \, \text{viii} \lambda \lambda 770, 780, \) and broad \( \text{Ly} \alpha \) (BLA). In gas in collisional ionization equilibrium (CIE), \( \text{O} \, \text{vi} \) reaches its peak ionization fraction at \( T \sim 3 \times 10^5 \) K. The strong \( \text{O} \, \text{vi} \lambda 1032, 1038 \) doublet lines can thus be a sensitive probe of gas at those collisionally ionized temperatures (Tripp et al. 2000; Savage et al. 2002; Danforth & Shull 2008; Lehner et al. 2009; Narayanan et al. 2010a, 2010b). However, \( \text{O} \, \text{vi} \) is also produced in low density environments under the influence of a strong radiation field through pure photoionization at \( T \sim 10^4 \) K (Savage et al. 2002; Prochaska et al. 2004; Lehner et al. 2006; Thom & Chen 2008b; Tripp et al. 2008; Oppenheimer & Dave 2009). In the case of most \( \text{O} \, \text{vi} \) absorption systems, the complexity seen in absorption prevents a reliable assessment of the process that dominates the ionization.

In comparison, the \( \text{Ne} \, \text{viii} \lambda \lambda 770, 780 \) doublet lines for an intervening absorber at low-\( z \) were reported by Savage et al. (2005), in the high signal-to-noise (S/N) \( \text{FUSE} \) Spectrum of the quasar 3C 263. The redshifted wavelengths \( \lambda \lambda 770, 780 \) can also be present in \( \text{O} \, \text{vi} \) absorbing gas at \( T \sim (0.5–1.5) \times 10^6 \) K. The temperature range corresponds to the warm phase of the WHIM. In CIE, the \( \text{Ne} \, \text{viii} \) ionization fraction peaks at \( T = 7 \times 10^6 \) K. The first clear detection (>3\( \sigma \)) of \( \text{Ne} \, \text{viii} \) doublet lines for an intervening absorber at low-\( z \) was reported by Savage et al. (2005), in the high signal-to-noise (S/N) \( \text{FUSE} \) Spectrum of the metal line system at \( z = 0.20701 \) toward HE 0226–4110. The column density of Ne viii and its ratio with \( \text{O} \, \text{vi} \) were consistent with an origin in collisionally ionized gas at \( T = 5.4 \times 10^5 \) K with a substantial baryonic column of \( N(\text{H}) \sim 8 \times 10^{19} \) cm\(^{-2} \). The intermediate ions (such as C iii, O iii, O iv, S iii) and strong H i absorption in this system were created in a separate gas phase at \( T \sim 2 \times 10^4 \) K through photoionization. The second detection of \( \text{Ne} \, \text{viii} \) was reported by Narayanan et al. (2009) in an intervening absorption-line system at \( z = 0.32566 \) in the \( \text{FUSE} \) Spectrum of the quasar 3C 263. The redshifted wavelengths of \( \text{O} \, \text{vi} \lambda \lambda 1032, 1038 \) lines in this absorber fell outside the wavelength coverage of \( \text{FUSE} \). Nonetheless, the detection of ions such as O iii, O iv, and N v in the \( \text{FUSE} \) Spectrum pointed to the presence of both photoionized and collisionally ionized regions in the absorber, traced by the intermediate ions and Ne viii, respectively. The detection of Ne viii required the presence of gas with \( T \gtrsim 10^5 \) K, corresponding to the temperature anticipated for the warm phase of the WHIM.

Here, we report another instance of Ne viii detection in an intervening absorption system in the low-\( z \) universe. The Ne vii i \lambda 770, 780 doublet lines are detected at high significance in the high S/N Hubble Space Telescope/Cosmic Origins Spectrograph (\( \text{HST}/\text{COS} \)) spectrum of the UV bright quasar PKS 0405–123. The detection distinctly points to the presence of warm collisionally ionized gas in a structure with a very large column density \( N(\text{H}) \gtrsim 10^{19} \) cm\(^{-2} \) of baryons. This is the third in a series of COS detections of collisionally ionized gas in the regions surrounding galaxies, the other two being Savage et al. (2010) and Narayanan et al. (2010b).

### 2. OVERVIEW OF PREVIOUS WORK

The PKS 0405–123 sight line was previously observed by the \( \text{FUSE} \) and \( \text{HST}/\text{STIS} \) instruments at spectral resolutions of \( \sim 20 \) km s\(^{-1} \) and \( \sim 7 \) km s\(^{-1} \). Lower resolution FOS observations (FWHM \( \sim 230 \) km s\(^{-1} \)) also exist for this target. A number of authors have published results on the detection and analysis of hydrogen and metal-line absorbers along this sight line (Bahcall et al. 1993; Jannuzi et al. 1998; Prochaska et al. 2004; Williger et al. 2006; Lehner et al. 2007; Tripp et al. 2008; Thom & Chen 2008a, 2008b; Howk et al. 2009). The most complete analysis of the ionization and chemical abundances in the \( z = 0.495096 \) absorber is given in Howk et al. (2009). A thorough investigation of the physical conditions was made possible by the combined \( \text{FUSE} \) and \( \text{STIS} \) coverage of several important low- and high-ionization metal species and hydrogen for this absorber.

In the \( \text{FUSE} \) spectrum, the Ne viii \lambda \lambda 770, 780 lines were non-detections with a 3\( \sigma \) upper limit on the equivalent width and column density of \( W(\text{Ne} \, \text{viii} \lambda \lambda 770) < 29 \) m\( \AA \) and log \( N(\text{Ne} \, \text{viii}) < 13.73 \) in the rest frame of the absorber (Howk et al. 2009). In the absence of Ne viii, Howk et al. (2009) were able to determine a single-phase photoionization model that could simultaneously explain the column densities of all ions, including O vi. The constraints from the photoionization models, particularly the metallicity, were found to be dependent on the nature of the ionizing spectrum. In the best-fit models, an extragalactic ionizing background dictated by QSOs predicts carbon and oxygen abundances of \( \sim 0.15 \) dex, whereas including the contribution of ionizing photons from star-forming galaxies, the abundances drop to \( \sim 0.62 \) dex. The single-phase photoionization models derived by Howk et al. (2009) predict densities of \( n(\text{H}) \sim 5 \times 10^{13} \) cm\(^{-3} \), baryonic column densities of log \( N(\text{H}) \sim 18.5 \), a photoionization equilibrium temperature of \( T \sim 28,000 \) K, and a physical size of \( L \sim 20 \) kpc for the absorbing region. Howk et al. (2009) also do not rule out the possibility of the absorber having multiple gas phases, with at least one phase of predominantly photoionized gas (\( T \sim 10^4 \) K) and another warmer phase (\( T \sim 10^6 \) K) that is collisionally ionized. The absence of Ne viii in the \( \text{FUSE} \) Spectrum was accepted as evidence for the lack of \( T \sim (0.5–3) \times 10^6 \) K warm–hot gas associated with the absorber. The detection of Ne viii in the higher sensitivity COS spectrum is a crucial new result, as it convincingly demonstrates that we are observing a substantial baryonic column of collisionally ionized gas, possibly the WHIM or the ionized halo of a galaxy.

### 3. COS OBSERVATIONS

The COS spectrum for PKS 0405–123 presented here is a combination of observations from the \( \text{HST} \) Early Release Program of 2009 August (Program ID: 11508) and GTO observations by the science team from 2009 December (Program ID: 11541). The details of the separate COS integrations are listed in Table 1. The exposures were retrieved from the \( \text{HST} \) archive and reduced in a uniform fashion using the most current CalCOS pipeline software (version 2.11). The reduced data were flux calibrated. The design capabilities of \( \text{HST}/\text{COS} \) are described in detail by Green (2001) and Froning & Green (2009) and in the updated COS Instrument Handbook (Dixon et al. 2010). The in-flight performance of COS is discussed by Osterman et al. (2010) and in the numerous instrument science reports on the STScI COS Web site. Sage et al. (2010) have used these COS observations of PKS 0405–123 to study the properties of the highly ionized plasma in the Lyman Limit system at \( z = 0.1671 \). The separate G130M and G160M grating integrations were combined together in flux units weighted by their respective

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5 http://www.stsci.edu/hst/cos/documents/isrs
Table 1

| HST ID     | Date of Observation (yyyy-mm-dd) | Grating | FP-POS | Central Wavelength (Å) | Wavelength Range (Å) | Exposure Duration (s) |
|------------|----------------------------------|---------|--------|------------------------|----------------------|-----------------------|
| LACB51010  | 2009-08-31                        | G130M   | 3      | 1291                   | 1136–1430            | 984b                  |
| LACB51020  | 2009-08-31                        | G130M   | 3      | 1300                   | 1147–1440            | 650                   |
| LACB51030  | 2009-08-31                        | G130M   | 3      | 1309                   | 1156–1449            | 1908                  |
| LACB51040  | 2009-08-31                        | G130M   | 3      | 1300                   | 1147–1440            | 650                   |
| LACB51050  | 2009-08-31                        | G130M   | 3      | 1318                   | 1165–1459            | 1908                  |
| LACB51060  | 2009-08-31                        | G130M   | 3      | 1300                   | 1147–1440            | 650                   |
| LACB51070  | 2009-08-31                        | G130M   | 3      | 1327                   | 1175–1468            | 1908                  |
| LB6822010  | 2009-12-21                        | G160M   | 3      | 1589                   | 1401–1761            | 2167                  |
| LB6822020  | 2009-12-21                        | G160M   | 3      | 1600                   | 1412–1772            | 2965                  |
| LB6822030  | 2009-12-21                        | G160M   | 3      | 1611                   | 1424–1784            | 2965                  |
| LB6822040  | 2009-12-21                        | G160M   | 3      | 1623                   | 1436–1796            | 2965                  |
| LB6823010  | 2009-12-21                        | G130M   | 1      | 1291                   | 1141–1435            | 1000b                 |
| LB6823021  | 2009-12-21                        | G130M   | 2      | 1291                   | 1138–1432            | 1400b                 |
| LB6823031  | 2009-12-21                        | G130M   | 3      | 1291                   | 1136–1430            | 1000b                 |
| LB6823041  | 2009-12-21                        | G130M   | 4      | 1291                   | 1133–1427            | 1430b                 |

Notes. Column 1 is the HST ID for the respective data set, Column 2 shows the date of observation, Column 3 lists the choice of grating, Column 4 gives the FP position used with the grating setting, Column 5 shows the grating central wavelength setting, Column 6 gives the wavelength range covered under each setting, and Column 7 lists the duration of integration. HST IDs dated 2009-08-31 are HST Early Release Observations (ERO) with program ID: 11508, and those dated 2009-12-21 are GTO observations with program ID: 11541 (PI: James Green).

* The data sets used in the co-addition to produce the spectrum at the redshifted wavelength of Ne vii λ770.

* The data sets used in the co-addition to produce the spectrum at the redshifted wavelength of Ne vii λ780.

In this section, we describe the observed properties of the z = 0.495096 absorption system. In Figure 1, we display the continuum normalized absorption profiles in the rest frame of the absorber and in Table 1, we list the basic line measurements. For consistency, we adopt the same redshift for the system as given in Howk et al. (2009), which was based on the centroid of the C ii λ977 profile from STIS. The COS spectrum for this system shows absorption from H i, O vii λλ1032, 1038, O iv λλ788, C iii λ977, O iii λλ833, and Ne vii λλ770, 780. In addition, it also covers wavelengths where absorption from C iv, N ii, Si ii, and Fe ii are expected. For the line measurements, we use the apparent optical depth (AOD) method of Savage & Sembach (1991). For Lyβ, O vi, O iv, and C iii we also apply Voigt profile models to estimate the column density, Doppler width and velocity associated with individual components. The fit models are shown in Figure 2. The profiles were fit with Voigt functions using the fitting routine of Fitzpatrick & Spitzer (1997). In this process, the model profiles were convolved with the COS instrumental spread function at the redshifted wavelength of the line. It is important that the specific LSF be used to fit the profile in order to minimize the impact of the LSF non-Gaussian wings on observed line profiles (see Ghavamin et al. 2009, for a detailed discussion). For completeness, we also show in Figure 1, the strong O v λ630 profile recorded at intermediate resolution by FUSE and the Lyα as seen by the low-resolution FOS. This is the first direct detection of O v in the IGM at low-z (Prochaska et al. 2004; Howk et al. 2009), and its absorption profile agrees well with the component structure for O vii seen in the COS data. The O vii λλ1032, 1038 lines in the high S/N COS spectrum agree generally with the higher resolution, lower S/N observation from STIS. The O vii absorption is spread over
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Figure 1. Continuum normalized spectrum of PKS 0405−123 showing absorption profiles and wavelength regions of some prominent lines in the $z = 0.495096$ metal line absorption system. The display is in the rest frame of the absorber, with $v = 0$ km s$^{-1}$ corresponding to $z = 0.495096$. All panels are showing HST/COS spectrum, except O vii $\lambda\lambda$1032, 1038, Ne viii $\lambda\lambda$770, 780, O iv $\lambda$788, C iii $\lambda$977, and O iii $\lambda$5007 which are covered by FUSE and FOS observations, respectively. The individual exposures used to produce the co-added COS spectrum are listed in Table 1. Ly $\beta$, O vi $\lambda$1032, 1038, Ne viii $\lambda\lambda$770, 780, O iv $\lambda$788, C iii $\lambda$977, and O iii $\lambda$5007 are COS detections of $>3\sigma$ significance. Features that are not part of the absorption system are marked “x” in each panel. The line measurements are listed in Table 2.

$\Delta v \sim 250$ km s$^{-1}$ and shows sub-component structure. In the STIS spectrum, a comparison of the apparent column density $N_a(v)$ profiles for the 1032 Å and 1038 Å lines had shown extra absorption in the 1038 Å line at $v \sim 30$ km s$^{-1}$, which was labeled as an unidentified interloping absorber (Howk et al. 2009).

In the COS spectrum, we do not find any marked difference between the velocity components of the O vii doublet lines (see Figure 3). The contaminating feature in O vi $\lambda$1038, found in the STIS spectrum, is more likely a spectral artifact.

The $N_a(v)$ comparison of Figure 3 shows that the O vi lines are subjected to saturation that is unresolved by COS. The difference in the integrated apparent column densities of log $N_a$(O vi 1032) = 14.39 ± 0.01, and log $N_a$(O vi 1038) = 14.48 ± 0.01 is significant and suggestive of this unresolved saturation. The O vi 1038 column density measurement is within ±1σ of the same by Howk et al. (2009) in the STIS spectrum and is likely to be a closer representation of the true column density. We correct for the line saturation effect using the procedure described in Savage & Sembach (1991) and obtain log $N_a$(O vi) = 14.48 ± 0.09 = 14.57. The 0.09 dex saturation correction corresponds to the difference between the logarithmic column densities of the weaker (less saturated) and stronger (more saturated) lines of the O vi doublet. The integrated O vi column density which we adopt in all subsequent analysis is the saturation corrected value of log $N_a$(O vi) = 14.57 ± 0.05 dex.

The multiphase nature of the absorber becomes evident while comparing the apparent column density profiles across the absorption seen in the intermediate ions (C iii, O iv) and the high ions (O v, O vi). The O iv and C iii velocity structures resemble each other, as revealed by the arrangement of their $N_a(v)$ profiles displayed in Figure 3. The absorption from these ions over the $-100$ km s$^{-1} \leq v \leq 30$ km s$^{-1}$ interval has a two component structure centered at velocities of $v \sim 0$ km s$^{-1}$ and $v \sim -30$ km s$^{-1}$. However, the component at $v \sim -30$ km s$^{-1}$ is not readily seen in O vi. It is likely that the slight asymmetry in the negative velocity portion of the O vi absorption is suggestive of an additional component, perhaps thermally broader than what is seen in O iv and C iii. Additional evidence for the multiphase nature of the absorber is evident from the difference between the weak absorption seen in C iii and O iv compared with the strong absorption in O vii over the velocity interval $30$ km s$^{-1} \leq v \leq 80$ km s$^{-1}$. This indicates that the gas in this velocity range has higher ionization, compared to the gas at negative velocity, although they are likely kinematically linked.
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Figure 1. (Continued)

Figure 2. Voigt profile fit models superimposed on the $z = 0.495096$ Ly$\beta$, O vi $\lambda 1032$, O iv $\lambda 788$, and C iii $\lambda 977$ lines seen in the COS spectrum of PKS 0405−123. The profiles were fit using the Fitzpatrick & Spitzer (1997) routine. For each line, the model profiles were convolved with the COS instrumental spread function at the redshifted wavelength. The fit results are tabulated in Table 2. The centroid of the individual absorption components is marked by the vertical tick marks in each panel. (A color version of this figure is available in the online journal.)
Figure 3. Apparent column density $N_a(v)$ profiles of the O\textsc{vi} $\lambda\lambda$1032, 1038 lines (top left panel), O\textsc{v} $\lambda$630 compared with O\textsc{vi} $\lambda$1032 (top right panel), O\textsc{vi} $\lambda$1032 compared with C\textsc{iii} $\lambda$977 (middle left panel), and O\textsc{vi} $\lambda$1032 compared with O\textsc{iv} $\lambda$788 (middle right panel). The $N_a(v)$ profiles are displayed in the rest frame of the $z = 0.495096$ absorber. All profiles except O\textsc{v} are COS observations. The O\textsc{v} $\lambda$630 is from FUSE. The difference in the apparent column densities between the individual lines of the O\textsc{vi} doublet is indicative of unresolved saturation as discussed in Section 4. The O\textsc{vi} $\lambda$1038 is contaminated at $v < -50$ km s$^{-1}$ by absorption unrelated to this system. The similarities between the component structures of O\textsc{v} and O\textsc{vi} is apparent and indicative of both ions predominantly tracing similar gas phase. The absorption in C\textsc{iii} and O\textsc{iv} in the velocity interval $20 \leq v \leq 70$ km s$^{-1}$ is weaker compared to O\textsc{v} and O\textsc{vi}. This could be due to higher ionization in the component of the gas producing the absorption. Apparent column density $N_a(v)$ profiles of the O\textsc{vi} $\lambda$1032 and Ne\textsc{vii} $\lambda$770 lines (bottom panel). The $N_a(v)$ comparison reveals the similarity in component structure between Ne\textsc{vii} and O\textsc{vi}, supporting the validity of the Ne\textsc{vii} detection and also suggesting that the two ions could be tracing similar gas phases.

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

to each other. The integrated column densities for O\textsc{iv} and C\textsc{iii} when compared to the STIS measurements suggest unresolved saturation for both lines. Howk et al. quote a lower limit of log $N_a$(O\textsc{iv}) $\gtrsim 14.37$ and log $N$(C\textsc{iii}) = 13.39 $\pm$ 0.05 adopted from component fitting. We adopt the same measurements for these two ions in our ionization analysis.

In the COS spectrum, O\textsc{iii} $\lambda$833 is detected at $>3\sigma$ significance. The line is very weak and therefore was undetected at the sensitivity afforded by FUSE. The velocity range over which O\textsc{iii} shows absorption concurs well with the velocity range of absorption from the higher ionization stages of oxygen. The rest-frame equivalent width $W_r$(O\textsc{iii} 833) = 33 $\pm$ 2 mÅ and column...
density log $N_{\alpha}(\text{O III}) = 13.73 \pm 0.03$ that we measure from the COS data are consistent with the upper limits of $W_r < 36 \text{ mÅ}$ and log $N_{\alpha} < 13.73$ obtained from FUSE by Howk et al. (2009). The errors on the O III equivalent width and column density do not include an estimated 5 mÅ and 0.06 dex systematic error produced by fixed pattern noise. With the detection of O III, we have column density measurements for four successive ionization stages of oxygen (O III–O VI), which sets useful constraints on the physical conditions in the absorber.

The information on H I associated with this absorber was poor in the existing STIS and FOS data. The FOS spectrum showed Lyα absorption at the redshift of the system, although the low resolution provided little information on the H I kinematics or the possibility of saturation. The Lyβ observed at higher resolution by STIS was poorly detected due to the low S/N $\sim 6$ pixel$^{-1}$ of the recorded spectrum. The COS data offer a factor of three higher S/N coverage of Lyβ, along with tighter constraints on the H I column density from the higher order lines of the Lyman series. The Lyβ feature in COS is a clear but weak detection, with a central optical depth of $\tau_{\text{max}}(v) \sim 0.3$. The H I is kinematically broad, spread over a velocity of $\Delta v \sim 350 \text{ km s}^{-1}$. Based on simultaneous fits to the Lyα (FOS), Lyβ (STIS), and Lyγ (STIS, $<3\sigma$ significance) features, Howk et al. (2009) derive an H I column density of $\log N(H I) = 14.29 \pm 0.10$. By integrating the $N_{\alpha}(v)$ profile of Lyβ in the COS spectrum, we estimate the logarithmic total H I column density as $14.21 \pm 0.02$, consistent with the STIS measurement. At the COS resolution, the Lyβ appears to have two components, a broader principal component at $v \sim -3 \text{ km s}^{-1}$ blended with a $v \sim 90 \text{ km s}^{-1}$ component which could be narrower than the instrumental width. This positive velocity component is weaker and may not contribute significantly to the total H I column density. The profile fit to COS Lyβ yields $b(H I) = 53 \pm 1 \text{ km s}^{-1}$ for the principal $v \sim -3 \text{ km s}^{-1}$ component. If the broadening of this component is dominantly thermal, then the implied temperature is $T = 1.7 \times 10^4 \text{ K}$. This component appears to be symmetric with respect to its centroid, although the COS instrumental resolution is not adequate to rule out of blending of closely separated components.

### 4.1. The Ne VIII λλ770, 780 Detection

The wavelengths of the redshifted Ne VIII λλ770, 780 lines are 1151.8 Å and 1166.2 Å, respectively. The Ne VIII λ770 line is therefore covered only by G130M grating observations at central wavelength settings of 1291 Å and 1300 Å. From the various COS integrations for this sight line, five exposures (with $t_{\text{exp}} \geq 1000 \text{ s}$) have central wavelength of $\lambda_c = 1291 \text{ Å}$, and six shorter exposures ($t_{\text{exp}} \sim 650 \text{ s}$) have $\lambda_c = 1300 \text{ Å}$. Similarly, the Ne VIII λ780 line is covered by G130M grating settings of central wavelengths 1291 Å, 1300 Å, 1309 Å, and 1318 Å.

The Ne VIII in this system is a relatively weak feature. To prevent gross systematic uncertainties from affecting the validity of the Ne VIII detection, we customized the combining of spectra in the wavelength range where absorption from the redshifted Ne VIII λλ770, 780 lines were expected. We carefully chose for co-addition only those individual exposures for which we could clearly rule out grid-wise shadows or other detector artifacts (at the redshifted wavelengths of the Ne VIII doublet lines). Choosing different central wavelength grating settings allows the dispersed light to shift across the detector in the dispersion direction. For each setting, this enables the recording of the same wavelength by different regions of detector. By then aligning in detector space the different integrations, it becomes possible to readily identify if the wavelengths corresponding to the Ne VIII λλ770, 780 lines in each exposure are affected by any fixed pattern structure. In the case of PKS 0405–123, the individual integrations had adequate S/N to carry out this selection process with some certainty.

The spectrum at the wavelength of the Ne VIII λ770 line is co-addition of four G130M integrations at the $\lambda_c = 1291 \text{ Å}$ setting, resulting in a total exposure time of 5.8 ks at $\sim 1151.8 \text{ Å}$. The IDs of these four exposures are labeled in Table 1. At the Ne VIII λ780 Å redshifted wavelength, we found all five G130M integrations with $\lambda_c = 1291 \text{ Å}$ setting free of strong fixed pattern noise features and thus suitable for co-addition. These exposure IDs are also labeled in Table 1. The Ne VIII λλ770, 780 lines displayed in the system plot of Figure 1 and the line measurements given in Table 2 are based on this revised co-addition.

By integrating over a 200 km s$^{-1}$ velocity interval, we measure a rest-frame equivalent width of $W_r = 45 \pm 6 \text{ mÅ}$ for the Ne VIII λ770 line. The significance of the detection is 7.5σ. The 1σ uncertainty listed here includes both statistical errors and continuum placement error. A more conservative estimate of the detection significance should take into account systematic uncertainty from fixed pattern features that contribute to the noise at the $\sim 5 \text{ mÅ}$ level. Including this systematic error, the Ne VIII λ770 is detected with a significance of 6.6σ.

At the location of the redshifted Ne VIII λ780 line, we also see absorption that is consistent with the 770 Å line. We measure a rest-equivalent width of $W_r(\text{Ne VIII 780}) = 29 \pm 5 \text{ mÅ}$ for this feature implying a detection significance of 5.8σ, excluding the systematic uncertainty from fixed pattern noise. The ratio $W_r(\text{Ne VIII 770})/W_r(\text{Ne VIII 780}) \approx 1.7$ is close to the expected 2:1 line strength ratio for a doublet, further validating the Ne VIII detection. The integrated apparent column densities obtained for the two Ne VIII lines are also within 1σ of each other. In subsequent analysis, we use log $N_{\alpha} = 13.96 \pm 0.06$ measured for the Ne VIII λ770 line as the Ne VIII column density in this absorber.

The rest-frame equivalent width we obtain for the Ne VIII λ770 of $W_r = 45 \pm 6 \text{ mÅ}$ is somewhat larger than the 3σ upper limit of $W_r < 29 \text{ mÅ}$ obtained from the lower S/N FUSE observations of Howk et al. (2009). We independently re-measured the FUSE observations integrating over $\pm 100 \text{ km s}^{-1}$ and obtain $W_r = 38 \pm 12 \text{ mÅ}$, which implies a 3σ detection. Our COS measurement is therefore in agreement with our new measurement of the FUSE spectrum. The validity of the COS detection of the Ne VIII λ770 line is further supported by the matching line profile observed for the much stronger O VI λ1032 line (see Figure 1(a)).

In Figure 3, we compare the apparent column density profiles of Ne VIII λ770 and O VI λ1032 lines. The $N_{\alpha}(v)$ plot reveals the similarity in component structure between Ne VIII and O VI. In particular, the strong absorption in O VI over the velocity interval $-70 \text{ km s}^{-1} \leq v \leq 25 \text{ km s}^{-1}$ is well matched by the absorption seen in the Ne VIII λ770 line. If the two ions are tracing similar gas phases, a similarity in their component structure is expected. The good velocity correspondence between the Ne VIII and O VI also lends support to the validity of the Ne VIII detection.

### 5. Ionization in the Absorber

Our primary goal is to understand the ionization mechanism responsible for the production of Ne VIII. Additionally, we investigate the extent to which other high ions such as O V...
and O vi are produced in the gas phase traced by Ne vili. We start the ionization discussion by considering the possibility of Ne vili arising in a purely photoionized gas.

5.1. Is the Ne vili Produced by Photoionization?

We use the photoionization code Cloudy (version C08.00; Ferland et al. 1998) to solve for time equilibrium models that reproduce N(Ne vili). We treat the other ionic column densities as upper limits to account for the possibility that the absorber could have a mix of gas phases at different ionization levels. The source of ionization is assumed to be dominated by the extragalactic background radiation at the redshift of the absorber, whose shape and intensity are as modeled by Haardt & Madau (2001). The UV background which we use has contributions from quasars and young star-forming galaxies. The photoionization models are calculated for different ionization parameters5 \( \log U \) and metallicities, to select the model that best fits the observations. We assume that the entire H1 column density of 14.21 dex which we measure for this system is associated with the photoionized gas that we model. This assumption need not be valid for a multiphase absorber. Therefore, we comment on how lower \( N(H) \) values in the Ne vili gas would change the ionization predictions. In the models, we have assumed that the relative elemental abundance ratios are solar, with abundances of [C/H]⊙ = −3.57 dex, [O/H]⊙ = −3.31 dex, [Ne/H]⊙ = −4.07 dex as given by Asplund et al. (2009).

In Figure 4, we display photoionization predicted ionic column densities for solar metallicity, log N(H1) = 14.21 and different log U. Recovering the observed Ne vili column density through photoionization requires very high ionization parameter values. The observed log \( N(\text{Ne vili})/N(\text{O vi}) \) ~ −0.6 is achieved at log \( U \sim −0.2 \) (for solar abundance pattern), which corresponds to a number density of \( n_H \sim 8 \times 10^{-6} \text{ cm}^{-3} \), and a total hydrogen column density \( N(\text{H}) \sim 6 \times 10^{19} \text{ cm}^{-2} \). Such diffuse gas with large total hydrogen column density results in a large physical size of \( L \sim 2.5 \text{ Mpc} \) for the photoionized region. If the absorption is from an unvirialized structure, then the large path length would result in line broadening due

5 Ionization parameter is defined as the ratio of the number density of photons with \( E \geq 13.6 \text{ eV} \) to the total hydrogen density.
Figure 4. Photoionization (PI) equilibrium models computed using Cloudy for log $N$(H\textsc{i}) = 14.21 and 10% solar metallicity. We assume in these models the most recent solar relative elemental abundance estimations of Asplund et al. (2009). The different curves show the column density predictions made by the PI models at different ionization parameter ($\log U$) values. The ionizing background is the Haardt & Madau (2001) model for $z = 0.495096$ which includes UV photons from quasars and young star-forming galaxies. The acceptable range of column densities for each ion, based on measurement, is highlighted in the photoionization curves using thick lines. The additional abscissa shows the predicted values for the number density ($n_H$), photoionization temperature ($T$), pressure ($P/K$), total hydrogen column density ($N(H)$), and path length ($L$). The column densities of O\textsc{vi} and Ne\textsc{viii} are simultaneously recovered for $\log U = -0.2$. The physical conditions predicted by this model are discussed in Section 5.1. (A color version of this figure is available in the online journal.)

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5.2. Evidence for $T \sim 5 \times 10^5$ K Gas

5.2.1. Collisional Ionization Equilibrium

If CIE applies, the apparent column density ratio of log $[N_{\text{Ne vii}}(\text{Ne \textsc{viii}})]/N_{\text{O vi}}(\text{O \textsc{vi}})] = -0.61$ will be true for an equilibrium temperature of $T \sim 4.7 \times 10^5$ K (assuming solar abundances). If there is contribution from the photoionized phase to the total O\textsc{vi} column density, then the constraint would be log $[N(\text{Ne vii})/N(\text{O vi})] > -0.61$, which is true for temperatures greater than $4.7 \times 10^5$ K. Thus, the presence of O\textsc{vi} provides a useful lower limit on the temperature of the gas producing a star-forming galaxy. On the other hand, for the ionization fraction of O\textsc{vi} and Ne\textsc{viii} to be altered, photons with energy $E \geq 113.9$ eV and $E \geq 207.3$ eV are required. O\textsc{vi} is produced at 113.9 eV and ionized at 138.1 eV. Similarly, Ne\textsc{viii} is produced at 207.3 eV and ionized at 239.1 eV. The radiative intensities of O and B stars at such high energies are very low due to the significant opacity from He$^+$ ionization edge at $E \geq 54.4$ eV. Thus, the O\textsc{vi} and Ne\textsc{viii} ionization levels are unlikely to be significantly altered by any local galactic radiation field.

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the Ne\textsc{viii} absorption. In gas at $T \gtrsim 4.7 \times 10^5$ K, only a small fraction of the hydrogen would be in the neutral form ($f_{\text{H}1} \lesssim N(\text{H}1)/N(\text{H}) = 6.83 \times 10^{-7}$; Gnat & Sternberg 2007). Also, the H\textsc{i} absorption arising in such gas would be thermally broadened to $b(\text{H}1) \gtrsim 88$ km s$^{-1}$. This implies that much of the Ly\textalpha absorption does not arise from the Ne\textsc{viii} phase, but from lower ionization gas that is predominantly photoionized.

To derive the total hydrogen content of the absorber and the metallicity in the collisionally ionized gas, the H\textsc{i} column associated with this higher ionization Ne\textsc{viii} phase has to be determined. However, the thermally broadened absorption from the trace neutral hydrogen associated with the Ne\textsc{viii} gas would fall on top of the stronger absorption from the photoionized gas. It is therefore difficult to separate out this shallow and broad component of H\textsc{i} from the observed Ly\textalpha profile. Therefore, one has to determine a column density upper limit for the broad H\textsc{i} indirectly. In Figure 5, we show the residual Ly\textalpha absorption after dividing the Ly\textalpha spectrum with the Voigt profile fit to feature. On top of this residual spectrum, we superimpose synthesized Ly\textalpha profiles with $b(\text{H}1) = 100$ km s$^{-1}$ and different column density values. It is evident from the figure that the broad H\textsc{i} associated with the Ne\textsc{viii} gas has to be log $N(\text{H}1) / N(\text{H}) \lesssim 13.5$ to be consistent with the data at the wavelength position of Ly\textalpha. We use this adopted upper limit on H\textsc{i} column density to determine the metallicity and the baryonic content in the Ne\textsc{viii} gas.

In Figure 6, we display Gnat & Sternberg (2007) CIE models for log $N(\text{H}1) = 13.5$. At $T = 4.7 \times 10^5$ K, the observed column densities of Ne\textsc{viii} and O\textsc{v} are well explained if we assume a metallicity of $[Z/H] = -0.35$. This CIE model would also account for $\lesssim 30\%$ of the O\textsc{v} column, but little O\textsc{iv} or O\textsc{iii}, consistent with their origin in a separate (photoionized) phase. The collisional ionization temperature and H\textsc{i} column density in the CIE model are lower and upper limits on the values they could assume. The observed Ne\textsc{viii} column density can be reproduced even when log $N(\text{H}1) < 13.5$ by increasing the metallicity to values above $-0.35$ dex. The H\textsc{i} ionization
fraction at $T = 4.7 \times 10^5$ K implies that the Ne viii gas is tracing a baryonic column of log $N(H) \geq 19.67$. This lower limit on baryonic column density will be smaller for metallicities higher than $-0.35$ dex. It is worth noting that the metallicity inferred for the collisionally ionized gas is consistent with the metallicity range of $-0.62 \lesssim [Z/H] \lesssim -0.15$ estimated by Howk et al. (2009) for the photoionized gas phase of this absorber.

Gas that is heated to very high temperatures can undergo rapid radiative cooling at $T \sim 10^8$ K due to enhanced cooling efficiencies (Gnat & Sternberg 2007). Over time, the ion fractions in such gas would begin to show departures from CIE due to faster radiative cooling rate compared to the rate at which recombinations occur. However, for the temperatures that we infer for the Ne viii gas, non-equilibrium ionization effects are minimal. At $T = 4.7 \times 10^5$ K, the Ne viii and O vii fractions in a radiatively cooling gas at solar metallicity are $f_{\text{Ne viii}} = 5.26 \times 10^{-2}$ and $f_{\text{O vii}} = 3.64 \times 10^{-2}$ (Gnat & Sternberg 2007). These values are only marginally different from the CIE values of $f_{\text{Ne viii}} = 4.87 \times 10^{-2}$ and $f_{\text{O vii}} = 3.72 \times 10^{-2}$, and therefore yield similar predictions for the physical conditions.

5.2.2. Collisional and Photoionization Hybrid Models

The CIE analysis described in the previous section did not take into account the incidence of extragalactic ionizing radiation on the absorber. Even when conditions are conducive for collisional processes to dominate the ionization, a realistic modeling of absorption systems should also take into account the influence on ionization by the isotropic radiation field from quasars and star-forming galaxies (Danforth et al. 2006; Richter et al. 2006; Tripp et al. 2008; Danforth et al. 2010a; Narayanan et al. 2010b). We use Cloudy to compute simple hybrid models that allow both collisional and photoionization reactions to contribute toward the ionization in the Ne viii gas phase. The temperature is fixed in Cloudy at $T = 4.7 \times 10^5$ K which is the lower limit on the temperature estimated from the CIE model for the Ne viii gas phase. The model that Cloudy would converge on will have the ionization and recombination reactions in equilibrium, even though the heating and cooling rates will be out of balance due to the fixed temperature.

In Figure 7, we show a hybrid of photoionization and CIE model curves for the Ne viii gas phase with log $N(H i) = 13.5$, $T = 4.7 \times 10^5$ K and different log $U$ values. Comparing the hybrid model column density predictions with the pure photoionization models displayed in Figure 4, we find that at log $U \lesssim -1.0$, the ionization fraction of both O vii and Ne viii is higher (and almost a constant) due to the collision of electrons with ions contributing to the ionization at higher densities (smaller log $U$). The metallicity in this hybrid phase can have a range of values between $-0.9 \lesssim [Z/H] \lesssim -0.3$. From the shape of the $N(O i v)$ curve in Figure 7, it is evident that the upper limit of $[Z/H] \sim -0.3$ dex is based on the assumption that the O vi is exclusively produced in the hybrid phase. At this metallicity, $N(\text{Ne viii})$ and $N(O i v)$ are simultaneously recovered for log $U < -2.2$, which corresponds to a density of $n_{\text{H}} \gtrsim 8 \times 10^{-4}$ cm$^{-3}$, total hydrogen column density of $N(H) \lesssim 5 \times 10^{19}$ cm$^{-2}$, and line-of-sight thickness of $L \lesssim 20$ kpc. For lower metallicities, log $U$ has to increase in order to recover the measured $N(\text{Ne viii})$. The lower limit on the metallicity is the value at which Ne viii is recovered near its peak in ionization fraction and at a log $U$ that does not result in an excessively large path length for the absorbing region. In the hybrid model, those conditions are satisfied for $[Z/H] \sim -0.9$ and log $U \sim -0.5$ which corresponds to $n_{\text{H}} \sim 8 \times 10^{-6}$ cm$^{-3}$.

6. GALAXIES IN THE VICINITY OF THE ABSORBER

Given the evidence for the presence of $T \sim 5 \times 10^5$ K gas, the location of the absorber with reference to galaxies becomes important. The absence of an optical counterpart to the absorber would strengthen the case for the absorption arising in an unvitrified WHIM structure in the IGM. Chen & Mulcheay (2009) have carried out imaging and spectroscopic search for galaxies in the PKS 0405–123 field. Their survey has a >60% completeness for galaxies brighter than $R = 22$ out to a separation of 2 arcmin from the line of sight, which corresponds to a projected distance of $734 h^{-1}_70$ kpc at $z = 0.4950$, assuming $\Omega_m = 0.28$ and $\Omega_{\Lambda} = 0.72$ (Wright 2006). The survey was 100% complete for galaxies brighter than $R = 20$. In this survey, a galaxy with rest-frame $R$ magnitude of $M_R \sim -5$ log $h_{70} = -19.6$ is identified close to the Ne viii absorber at a projected distance of $\rho = 110 h_{70}^{-1}$ kpc. The galaxy’s spectroscopic redshift is $z = 0.4942$, and thus is at a systemic velocity of $\Delta v = -180$ km s$^{-1}$ with respect to the Ne viii absorber. No other galaxy brighter than $R = 20$ is identified within a comoving distance of $3.7 h_{70}^{-1}$ Mpc of the absorber. At this redshift, $M_R = -19.6$ corresponds to a galaxy luminosity of $0.08 L^*_R$ (Dahlen et al. 2005).
The galaxy displays an extended morphology in the high spatial resolution HST/WFPC2 image of the field (see Figure 10 of Chen & Mulchaey 2009). The galaxy’s spectrum is dominated by strong emission lines from [O II], [O III], Lyβ, and Lyβ indicating activity in the underlying stellar population. The proximity of the Ne viii absorber to the galaxy is an important, though not conclusive, indicator of the absorption possibly arising in the extended hot halo of the galaxy. In the case of the z = 0.20701 Ne vii system toward HE 0226–4110 reported by Savage et al. (2005), three sub-L* galaxies were identified within ρ = 200 kpc and Δv = 300 km s−1 of the absorber (Mulchaey & Chen 2009). Both these Ne vii detections also show strong O vi absorption (W = 30 mÅ). It is known from a number of absorber-galaxy studies that O vi systems preferentially arise within the ρ ≲ 500 kpc environment of L* galaxies and even closer to 0.1L* galaxies (Sembach et al. 2004; Tumlinson et al. 2005; Stocke et al. 2006; Tripp et al. 2006; Lehner et al. 2009; Wakker & Savage 2009; Chen & Mulchaey 2009). If Ne viii is always associated with strong O vii systems, then they are also likely to be tracing collisionally ionized gas in circumgalactic environments. Investigating this correlation requires a large sample of Ne vii detections.

The [Z/H] ≈ −0.6 dex metallicity derived from the hybrid model for this Ne viii absorber is more consistent with a halo origin rather than in the canonical WHIM structure tracing pristine IGM distant from galaxies, in which case lower metallicities are expected (Danforth et al. 2006). It is however important to bear in mind that the regions where galaxies interface with the IGM are complex environments influenced by a variety of inflow and outflow processes transferring matter and energy between the two systems. This blurs the distinction between what can be characterized as the halo or the IGM. It is difficult to be conclusive about the astrophysical origin of an absorption system based solely on one-dimensional information obtained by probing a pencil beam through such a complex environment.

6.1. Summary

We have reported on the detection of Ne viii λλ770, 780 lines in the intervening absorption system at z = 0.495096 in the COS high S/N spectrum of the quasar PKS 0405−123. This is the third clear detection of this ion in the low-z IGM. The significant results are summarized as follows.

1. Both members of the Ne vii doublet in the z = 0.495096 multiphase absorber are detected at high significance (above the 5σ level) in the COS spectrum. The Ne vii λ770 line has a rest-frame equivalent width of Wv = 45 ± 6 mÅ and an apparent column density of log Nv = 13.96 ± 0.06, and the Ne vii λ780 line has Wv = 29 ± 5 mÅ and log Nv = 14.08 ± 0.07. The Ne viii absorption extends over the same velocity interval as the strong absorption from O vii λλ1032, 1038 lines.

2. Also seen in the COS spectrum are Lyβ, C iii, O iii, O iv, and O vi associated with the absorber. The O iii line was a non-detection at the 3σ significance level in the FUSE spectrum for this target. We measure Wv(O iii λ333) = 33 ± 2 mÅ and log Na(O iii) = 13.73 ± 0.03. The Lyβ absorption was poorly detected in the low S/N STIS spectrum. The higher sensitivity spectrum for Lyβ afforded by COS reveals subcomponent structure in H i, with an integrated apparent H i column density of log Nh(H i) = 14.21 ± 0.02.

3. The column density of Ne viii cannot be explained by gas that is purely photoionized by the extragalactic ionizing background radiation field. The detection of Ne viii requires collisionally ionized gas with T = 5 × 10^4 K. Gas at this temperature is highly ionized with a trace neutral H i fraction of fH = N(H i)/N(H) ≈ 7 × 10^−7. From the Lyβ profile, we estimate the H i column in this warm collisional phase to be log N(H i) ≲ 13.5, which suggests that the Ne viii is tracing a gas structure with a total hydrogen column density of N(H) ≈ 5 × 10^19 cm−2.

4. Hybrid models that simultaneously take into account both collisional ionization and photoionization reactions predict a metallicity of [Z/H] = −0.6 ± 0.3 dex in the Ne viii gas phase. The density in this gas phase is constrained to nH ≲ 10−5 cm−3 and total hydrogen column density N(H) ≈ 1019−1020 cm−2. Even in the hybrid models the production of Ne viii is through collisional ionization.

5. The O vi and O vii absorptions are consistent with a multiphase origin, with contributions from both the T ≈ 10^4 K photoionized gas traced by the H i, C iii, O iii, and O iv and the T ≈ 5 × 10^4 K collisionally ionized gas phase where the Ne viii is produced. The metallicity for the collisionally ionized gas phase is consistent with the −0.62 ≲ [Z/H] ≲ −0.15 metallicity range estimated by Howk et al. (2009) for the photoionized gas phase in this absorber.

6. The Chen & Mulchaey (2009) imaging survey of the PKS 0405−123 field has identified a galaxy with rest-frame R magnitude of M_R = −20.0 log h_70 = −19.6 (L ≈ 0.8L_∗) at a projected separation of ρ = 110h_70^{-1} kpc and at a systemic velocity of Δv = −180 km s−1 from the Ne viii absorber. The proximity of the absorber to the galaxy and their modest velocity displacement from each other suggests the possibility of the Ne viii absorption arising in multiphase gas embedded in the hot halo of the galaxy. The physical properties and metallicity of the absorber are also consistent with an origin in a nearby intergalactic WHIM structure.

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