THE ORIGIN OF A CHEMICALLY ENRICHED Lyα ABSORPTION SYSTEM AT z = 0.167

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ABSTRACT

We present the first detailed analysis of the chemical abundances, ionization state, and origin of a partial Lyman limit system \([\text{N}(\text{H} \, \text{i}) \approx 10^{16} \, \text{cm}^{-2}]\) at low redshift (\(z = 0.167\) toward PKS 0405–1219). Two galaxies at an \(\approx 70 \, h^{-1} \, \text{kpc}\) projected distance to the QSO have been identified at the absorber redshift. We analyze an echelle spectrum of the QSO obtained with the Space Telescope Imaging Spectrograph and find that this absorption system exhibits associated lines produced by C⁷⁺, N⁷⁺, O⁷⁺, Si⁷⁺, Si⁸⁺, Fe⁷⁺, and Fe⁸⁺ and, most interestingly, O⁷⁺ and N⁷⁺. The results of our analysis show that the partial Lyman limit system traced by various ions is likely to be embedded in a collisionally ionized O vi gas of larger spatial extent. Furthermore, the partial Lyman limit system appears to have a metallicity of at least 1/10 solar and is most likely solar or supersolar despite the fact that no luminous galaxies are seen within a projected distance \(\rho = 60 \, h^{-1} \, \text{kpc}\) to the QSO. Finally, adopting the temperature estimated for the hot gas \((7 \approx 2.5 \times 10^{7} \, \text{K})\) and assuming a simple isothermal halo, we estimate a gas mass of \(1.5 \times 10^{12} \, M_{\odot}\) and a gas number density \(\approx 3 \times 10^{-3} \, \text{cm}^{-3}\).

Subject headings: galaxies: evolution — quasars: absorption lines

1. INTRODUCTION

The absorption-line systems observed in the spectra of background QSOs have proved to be a sensitive probe to the physical conditions of intervening gas. In particular, kinematic studies and chemical abundance measurements of Lyα absorption systems of neutral hydrogen column density \(\text{N}(\text{H} \, \text{i}) \geq 10^{16} \, \text{cm}^{-2}\) at \(z > 1.7\) provide a direct assessment of the dynamical characteristics and chemical-enrichment history of the absorbers (Prochaska & Wolfe 1997, 1998, 1999, 2000; Pettini et al. 1997; Rauch, Haehnelt, & Steinmetz 1997; Haehnelt, Steinmetz, & Rauch 1998; Prochaska 1999). While these absorption systems are generally believed to originate in or near galaxies (because of a high H i column density and/or a large metal content), it has been extremely difficult to associate the properties of absorption-line systems directly with the properties of galaxies because distant galaxies are faint. On the other hand, at redshift \(z \lesssim 1\), where galaxies are routinely identified, various galaxy surveys targeted at QSO fields have shown that luminous galaxies possess extended Mg ii gas out to \(\approx 40 \, h^{-1} \, \text{kpc}\) (e.g., Bergeron & Boissé 1991), extended C iv gas out to \(100 \, h^{-1} \, \text{kpc}\) (Chen et al. 2000), and extended neutral hydrogen gas out to \(\approx 180 \, h^{-1} \, \text{kpc}\) (Lanzetta et al. 1995; Chen et al. 1998; H.-W. Chen, K. M. Lanzetta, J. K. Webb, & X. Barcons 2000, in preparation). But the origin and physical environment of the extended gas is largely unknown because of the limited information regarding the kinematics and metallicity of the gas. The primary difficulty arises in acquiring a high-quality QSO spectrum of wide UV spectral coverage.

To address this issue, we are initiating a survey of Lyα absorption systems for which high-resolution, high signal-to-noise ratio (S/N) UV spectra are available and for which the absorbing galaxies have been identified. In this Letter, we present the first results of this survey based on the study of a Lyα absorption system at \(z = 0.167\) toward PKS 0405–1219 (\(z_{\text{sys}} = 0.5726\)), for which high-quality echelle spectra have been obtained with the Hubble Space Telescope (HST) using the Space Telescope Imaging Spectrograph (STIS). This system is especially interesting for two reasons. First, previous measurements show that this system has a rest-frame Lyα absorption equivalent width of \(0.65 \, \text{Å}\), implying an H i column density \(\text{N}(\text{H} \, \text{i}) = 10^{15.3} \times 10^{176} \, \text{cm}^{-2}\) for a reasonable range of Doppler parameters (H.-W. Chen, K. M. Lanzetta, J. K. Webb, & X. Barcons 2000, in preparation). This suggests that the absorber is a partial Lyman limit system at \(z \approx 0\), which may provide a benchmark for comparison against Lyman limit systems (LLSs) at high redshift. Second, two galaxies have been identified at the absorber redshift (Spinrad et al. 1993; H.-W. Chen, K. M. Lanzetta, J. K. Webb, & X. Barcons 2000, in preparation). A detailed study of this absorption system therefore serves to constrain the physical properties of the galaxy environment, which offers a unique opportunity to investigate whether QSO absorption-line systems arise in extended halos of individual galaxies or in intragroup media of galaxy groups.

2. ANALYSIS

Spectroscopic observations of PKS 0405–1219 were accessed from the HST data archive. The QSO was observed with HST using STIS in echelle mode with a 0.′2 × 0.′06 slit and the E140M grating \((R = 45,800\) or \(6.7 \, \text{km} \, \text{s}^{-1}\)) for a total exposure time of 27,208 s. The observations were carried out in two visits of five exposures each. The individual echelle spectra were reduced, extracted, and calibrated using standard pipeline techniques and were co-added to form an averaged spectrum and a \(1 \, \sigma\) error array per visit using our own reduction program. To form a final spectrum for absorption-line studies, we normalized each co-added spectrum with a best-fit, low-order polynomial continuum and calculated a weighted average of the normalized spectra with the weighting factor determined by the squares of the S/N. The final spectrum covers a spectral range of 0.3–2.5 μm.

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1 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 NAS5-26555.

2 We adopt a standard Friedmann cosmology of dimensionless Hubble constant \(h = H_{0}/(100 \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1})\) and deceleration parameter \(q_{0} = 0.5\) throughout this Letter.
Fig. 1.—Velocity profiles of absorption lines identified for the absorption system at $z = 0.167$ in the STIS spectrum with $v = 0$ corresponding to redshift $z = 0.1671$. The identification of each transition is indicated in the lower right-hand corner of each panel. The top and bottom dashed lines indicate the continuum and zero levels, respectively. The dash-dotted lines indicate the velocity centroids. Contaminating features from other sources that are excluded in our analysis are indicated by dotted curves.

We identified absorption features produced by H, C, N, O, Si, Si, Si, and possibly Fe and Fe; most interestingly, we identified the absorption doublets produced by N and O for the absorption system at $z = 0.167$. Figure 1 shows the velocity profiles of all transitions with corresponding to redshift $z = 0.1671$.

We first determined the column density by fitting Voigt profiles to the saturated Ly and Lyb absorption lines using the VPFIT package provided by R. Carswell and J. Webb. But because of the degeneracy between $b$ and the Voigt profiles, we found that while the profile-fitting procedure yielded a best fit $N(H\,i) = 10^{15.8(+0.2)}$ to $b = 35$ km s$^{-1}$, solutions with similar reduced range from $12 < \chi^2 < 13$ and $b$ from 36 to 26. Additional spectroscopic observations of the QSO in the far-UV wavelength range (e.g., with the Far-Ultraviolet Spectroscopic Explorer) are required to measure the H i column density precisely using higher order Lyman series absorption. Despite the large uncertainty in the column density, we confirmed that the absorber is a partial LLS with $N(H\,i) = 10^{16}$ cm$^{-2}$. Next, we measured the ionic column densities using the apparent optical depth method (Savage & Sembach 1991), which provides an accurate column density estimate for resolved, unsaturated absorption lines. The column density measurements are presented in Table 1, which lists the ions, the corresponding rest-frame absorption wavelength $\lambda$, and the estimated column densities together with the associated errors in the first three columns.

### TABLE 1

| Species | $\lambda_0$ (Å) | $\log N$ (cm$^{-2}$) | $b$ (km s$^{-1}$) | [X/H]$^a$ |
|---------|-----------------|----------------------|------------------|----------|
| H i …… | 1025.72 >15.7   | 34.7 ± 2.5           | …                | …        |
| C ii …..| 1036.79 >14.10  | 35.7 ± 0.09          | …                | …        |
| N ii …..| 1083.99 >14.25  | 11.6 ± 1.0           | 0.9              | 0.27     |
| N v ……  | 1238.82 13.84 ± 0.07 | 50.2 ± 7.0          | …                | …        |
| O i ……  | 1302.17 13.91 ± 0.06 | …                  | …                | …        |
| O vi …… | 1301.93 14.67 ± 0.16 | 72.6 ± 4.9          | …                | 0.25     |
| Si ii ….| 1190.42 13.22 ± 0.07 | 9.9 ± 0.9           | …                | …        |
| Si iii …| 1193.29 13.29 ± 0.05 | …                  | …                | …        |
| Si iv ….| 1260.42 13.16 ± 0.12 | …                  | …                | …        |
| Si iii …| 1206.50 13.33 ± 0.12 | …                  | …                | …        |
| Si iv ….| 1393.76 13.18 ± 0.05 | …                  | …                | …        |
| Si iii …| 1402.77 13.49 ± 0.07 | …                  | …                | …        |

$^a$ [X/H] is defined as $\log N(X)/N(H) - \log [X/H]_0$. We assumed that $\log N(H\,i) = 16.5$ for the abundance estimates. Increasing (decreasing) $N(H\,i)$ by 0.5 dex decreases (increases) the abundance measurements by 0.5 dex.

$^b$ The solutions included additional components in the blue wing of the Ly$\alpha$ line that do not impact the $N(H\,i)$ of the absorption system at $z = 0.167$. 
The detections of N$^{+4}$ and O$^{+5}$ at the absorber redshift are very interesting because these ions are often believed to form through collisional ionization in hot gas clouds. We show in Figure 1 that all the ions except N$^{+4}$ and O$^{+5}$ have consistent profile signatures that trace the partial LLS, while the N vi and O vi doublets appear to be broad and have velocity centroids blueshifted by ≈30 km s$^{-1}$ from the other ions. The differences in kinematic signatures strongly indicate that the N vi and O vi doublets and the partial LLS traced by the other ions do not arise in the same regions. For this reason, we studied the physical environment separately for the two gas regions.

We first determined the temperature of the partial LLS using the $b$ parameters estimated from a Voigt profile analysis for the unsaturated lines produced by Si$^{+}$ and N$^{+}$. The estimates of the $b$ parameters are presented in the forth column of Table 1. We found that $b = 9.9 ± 0.9$ km s$^{-1}$ for Si$^{+}$ and that $b = 11.6 ± 1.0$ km s$^{-1}$ for N$^{+}$. Because both thermal motion and bulk motion contribute to the measured Doppler parameter and because Si$^{+}$ and N$^{+}$ share the same bulk motion, we solved for $b_{\text{bulk}}$ and $T$. We found that $b_{\text{bulk}} = 6.8 ± 2.9$ km s$^{-1}$ and that $T ≈ 7.4 × 10^4$ K, with a 1 σ lower limit being $T ≈ 2.7 × 10^4$ K and a 1 σ upper limit being $T ≈ 1.5 × 10^5$ K.

According to Sutherland & Dopita (1993), collisional ionization models cannot produce the observed relative abundances for the Si ions at temperatures between $T ≈ 2.7 × 10^4$ K and $T ≈ 1.5 × 10^5$ K. It is therefore very unlikely that the partial LLS is collisionally ionized. We determined the ionization state of the partial LLS by comparing the column densities of H$^0$, Si$^{+}$, Si$^{+3}$, and Si$^{+3}$ with the predictions from a series of photoionization models calculated using the CLOUDY software package (Ferland 1995). Considering a plane-parallel geometry for gas of solar metallicity, we calculated the column density predictions for various ions. The predictions of relative ionic column densities are fairly insensitive to the adopted metallicity and H$^0$ column density (for optically thin gas) in the CLOUDY calculations, even though the absolute predictions may vary accordingly. Therefore, we were able to place reasonably tight constraints on the ionization parameter, which is the ratio of incident ionizing photons to the total hydrogen number density, $U = \Phi_{\text{ion}}/n_H$, by comparing the relative abundances of the Si ions. We found $log U = −2.64 ± 0.07$ using the Si$^{+}$/Si$^{+3}$ ratio, which is in a good accordance with the limits derived from Si$^{+}$/Si and Si$^{+}$/Si$^{+3}$. Given the best estimated $U$, we determined the total hydrogen column density N(H), ionization fraction $x$, hydrogen number density $n_H$, and the spatial extent for the partial LLS. The results are summarized in Table 2.

Finally, we estimated the elemental abundances of the partial LLS using the ionization fraction correction calculated from the CLOUDY model for an ionization parameter $log U = −2.64$. The results are shown in the last column of Table 1 for an H I column density log $N$($\text{H}$ I) = 16.5. Adopting the largest possible H I column density log $N$($\text{H}$ I) = 10$^{17}$ cm$^{-2}$, we found that the partial LLS would have 1/10 solar abundance determined for carbon and silicon and 1/5 solar abundance for nitrogen. Adopting the best-fit N($\text{H}$ I) of 10$^{15.2}$ cm$^{-2}$, we derived a supersolar metallicity for the system. In addition, we also estimated the chemical abundance using the O I absorption line. In regions where the resonant charge-exchange reaction between oxygen and hydrogen becomes dominant, the column density ratio O I/ H I provides a direct estimate of the elemental abundance of oxygen. Otherwise, the ratio O I/ H I provides a lower limit to the estimate of the oxygen elemental abundance. We derived a metallicity of at least 1/2 solar abundance for oxygen and contend that the absorbing gas has been heavily enriched in metals.

The results obtained from the CLOUDY analysis demonstrated that a single photoionization model cannot explain the observed column densities of the O$^{+5}$ and N$^{+4}$ ions. At the extreme upper limit log $U = −2.2$, both O vii and N vi are predicted to be at least 0.4 dex less abundant than Si vi. But our measurements indicate that O vii and N vi are at least 0.4 dex more abundant than all the Si ions. In agreement with our assessment of the kinematic characteristics, the CLOUDY predictions further demonstrated that O$^{+5}$ and N$^{+4}$ do not arise in the partial LLS. Under the assumption of collisional ionization, the temperature of O$^{+5}$ and N$^{+4}$ may be derived by comparing their column density ratio with a series of collisional ionization models. According to Shapiro & Moore (1976), an optically thin gas of solar relative abundance at thermal equilibrium with N($\text{O}$ vi)/N($\text{N}$ vi) = 6.9 ± 1.5 has a temperature of $T = (2.6 ± 0.1) × 10^4$ K. At this temperature, we calculated the total hydrogen column density using the ionization fraction correction calculated by Sutherland & Dopita (1993). We also estimated the bulk motion of these ions by fitting Voigt profiles to the O vii and N vi absorption doublets. The results are summarized in Table 2.

## 3. DISCUSSION

Our analysis of the STIS echelle spectrum revealed unusual properties of the Lyα absorption system at $z = 0.167$. We found a chemically enriched, warm gas region giving rise to the partial LLS and a hot gas region giving rise to O$^{+5}$ and N$^{+4}$ along the QSO line of sight. Two galaxies have been identified in the field of PKS 0405–1219 at the absorber redshift (Spinrad et al. 1993; H.-W. Chen, K. M. Lanzetta, J. K. Webb, & X. Barcons 2000, in preparation): (1) an elliptical galaxy at $z = 0.1667$ with an angular distance of $\theta = 40.4$ arcsec to the QSO (corresponding to an impact parameter $\rho = 74.9$ h$^{-1}$ kpc) and a rest-frame K-band luminosity $L_K = 1.20L_\odot$ and (2) a spiral galaxy at $z = 0.1670$ with $\theta = 33.9^\prime$ (corresponding to $\rho = 62.8$ h$^{-1}$ kpc) and $L_K = 0.02L_\odot$. While it is not uncommon to find tenuous gas at large galactic distances ($\rho \sim 100$ h$^{-1}$ kpc) around nearby elliptical galaxies (e.g., Fabbiano, Kim, & Trinchieri 1992) or

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### Table 2: Physical Parameters of the Absorption System at $z = 0.167$

| Physical Parameter | Partial LLS$^a$ | N v, O vi$^b$ |
|--------------------|----------------|--------------|
| Ionization parameter log $U$ | $−2.64 ± 0.07$ | ... |
| Ionization fraction $x$ | 0.996 | ... |
| Hydrogen column density log $N$(H) | $18.86 ± 0.07$ | $≈18.6$ |
| Hydrogen number density $n_H$ (cm$^{-3}$) | $6 × 10^4$ | $<3 × 10^5$ |
| Cloud size $l$ (kpc) | $≈4$ | ... |
| Bulk motion $b_{\text{bulk}}$ (km s$^{-1}$) | $≈7$ | $≈70$ |
| Temperature $T$ (K) | $7.4 × 10^4$ | $2.5 × 10^4$ |
| Chemical abundance [Z/H] | $>−0.1$ | ... |

$^a$ Adopting an ionizing radiation intensity $J_{\text{ion}} = 2 × 10^{−12}$ ergs s$^{-1}$ Hz$^{-1}$ sr$^{-1}$ at $z = 0$ estimated by Shull et al. 1996.

$^b$ N(H) was estimated based on the measured O vi column density, corrected for the ionization fraction of oxygen at $T \sim 5.4 × 10^4$ K by assuming a solar abundance; $n_H$ was estimated by requiring a cooling time comparable to or greater than the dynamical time.

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4 The error in $U$ is based solely on the error in N(Si vi)/N(Si iv) and does not account for the systematic errors associated with the simplified assumptions inherent to the CLOUDY calculations.

5 The estimated temperature may differ by only $≈5\%$ if the relative abundance of oxygen to nitrogen is twice the solar value.
groups of galaxies (e.g., Mulchaey et al. 1996), it is very surprising to find metal-enriched, high column density gas at this large distance. Furthermore, our column density estimates for O\textsuperscript{\textsc{ii}} and N\textsuperscript{\textsc{ii}} are comparable to the measurements obtained for highly ionized gas in the Galactic halo, most of which is believed to arise near the galactic plane (Savage, Sembach, & Lu 1997; Savage et al. 2000). The spectral characteristics of the elliptical galaxy exhibit signs of recent star formation (Spinrad et al. 1993); therefore, the physical process that initiated the recent star formation might be responsible for transporting metals to large galactic distances.

In light of the different kinematic characteristics between the partial LLS and the O\textsc{vi} absorbing cloud, it seems likely that the partial LLS is embedded within a larger volume of hot O\textsc{vi} gas that is spread out in a galactic halo or an intragroup medium. But it is very rare to detect hot gas at a temperature $T \approx 2 \times 10^4$ K, where the cooling function is the most effective (see, e.g., Spitzer 1978). In order for the hot gas to remain at this temperature, we derive rough estimates of the underlying mass and gas number density by assuming a simple isothermal halo. Specifically, a more massive system would have a higher virial temperature and consequently raise the gas temperature through gravitational interaction. A higher gas density would increase the cooling rate and consequently lower the gas temperature through collisional cooling processes. We estimate the mass of the galaxy or galaxy group that supports the extended hot gas by requiring a virial temperature $T \approx 2.5 \times 10^4$ K and find a total mass of $M \approx 1.5 \times 10^{12} M_\odot$ for a half-mass radius $r_h \approx 0.35$ Mpc. We estimate the number density by requiring a cooling time longer than the dynamical time, $t_{\text{dyn}} \approx \pi R / \sqrt{2} \sigma$, and we find that the number density of the absorbing gas should be $n \approx 3 \times 10^{-5}$ cm$^{-3}$ for a velocity dispersion $\sigma \approx 60$ km s$^{-1}$ at $R \approx 100$ kpc (implying $t_{\text{dyn}} \approx 3.5$ Gyr).

Although two galaxies have been identified at the absorber redshift, it is very difficult to determine whether the absorbing gas originates in extended halos of individual galaxies or in an intragroup medium of an underlying galaxy group without a more complete spectroscopic survey of galaxies in this field. We can, however, derive constraints on the properties of the galaxies either individually or collectively for both scenarios based on all the available measurements.

A comparison of galaxies and Ly\textsc{a} absorption systems along common lines of sight has shown that the gaseous extent $r$ of galaxies of all morphological types scales with galaxy $K$-band luminosity $L_K$ according to $r \propto L_K^{0.53 \pm 0.08}$ (H.-W. Chen, K. M. Lanzetta, J. K. Webb, & X. Barcons 2000, in preparation). According to these authors, we expect that the extended gas of the spiral galaxy would contribute an H\textsc{i} column density of no more than $3.2 \times 10^{14}$ cm$^{-2}$ at $\rho = 62.8$ h$^{-1}$ kpc but that the extended gas of the elliptical galaxy would easily contribute an H\textsc{i} column density of $10^{15}$ cm$^{-2}$ at $\rho = 74.9$ h$^{-1}$ kpc. By carefully examining deep images obtained both with the HST using the Wide Field Planetary Camera 2 with the F702W filter and with the Infrared Telescope Facility 3 m telescope using the $K'$ filter, we find that if there are unidentified dwarf galaxies at the absorber redshift and closer to the QSO line of sight, then they cannot be brighter than 0.02$L_K$. It is therefore more likely that the absorbing clouds should follow the halo motion of the bright elliptical galaxy if the absorption system arises in individual galactic halos. Assuming that the absorption system is produced in the gaseous halo of the elliptical galaxy and adopting a King profile for the gas distribution around the elliptical galaxy, $n(r) \propto 1/[1 + (r/r_c)^2]$, we derive a total gas mass of $M_{\text{gas}} \approx 10^{10}$ $M_\odot$ within a radius $r < 100$ h$^{-1}$ kpc for a core radius between $r_c = 10$ and 50 kpc and for a unit filling factor. The estimated gas mass within 100 h$^{-1}$ kpc is significantly lower than the dynamical mass of $3.6 \times 10^{11}$ $M_\odot$ estimated for $M/L_K \approx 6.6$, implying a small gas fraction in the inner part of the elliptical galaxy.

Mulchaey et al. (1996) suggested that an intragroup medium of a temperature just below the detection threshold of existing X-ray observations may reveal itself through the imprint of high-ionization absorption lines, such as O\textsc{vi} and Ne \textsc{vii}, in the spectra of background QSOs. Recent observations also indicated that some O\textsc{vi} absorption lines originate in an environment of excess galaxy counts (Tripp, Savage, & Jenkins 2000). Adopting the $\alpha$-$T$ correlation obtained for groups of galaxies in X-ray (Mulchaey & Zabludoff 1998) and extrapolating to lower temperature, we find a corresponding velocity dispersion of $\sigma \approx 60$ km s$^{-1}$ for $T \approx 2.5 \times 10^4$ K, which is very close to the estimated bulk motion for the O\textsc{vi} absorbing gas. Based on the estimated velocity dispersion, we derive a total mass of $M \approx 1.5 \times 10^{12} M_\odot$ for the galaxy group by assuming a virialized isothermal halo and a half-mass radius $r_h \approx 0.35$ Mpc. Therefore, we find that if the absorption system is produced in the intragroup medium, then the total mass of the underlying galaxy group is comparable to the Local Group (Courteau & van den Bergh 1999).

The absorber at $z = 0.167$ exhibits a striking resemblance to the LLS at $z = 0.79$ presented by Bergeron et al. (1994) both in physical properties of the absorbing gas and in the surrounding galaxy environment. The absorber at $z = 0.79$ was found to have a metallicity of a half-solar and is likely embedded in a hot O\textsc{vi} gas of $T \approx 2 \times 10^4$ K. A group of galaxies have been identified at the absorber redshift, the closest of which is at 110 h$^{-1}$ kpc to the QSO line of sight. If the two systems are representative of low-redshift LLSs, then the relationship between LLSs and surrounding galaxies may provide important clues regarding the chemical-enrichment history and dynamics of gas in intragroup media. On the other hand, various models have been proposed to explain extended H\textsc{i} gas at large galactic distances, including satellite accretion (Wang 1993), tidal debris (Morris & van den Bergh 1994), and two-phase galactic halos (Mo & Miralda-Escude 1996). Of these models, accretion from a star-forming satellite galaxy is the most likely to explain the observed high-metallicity gas at large distances to regular-looking galaxies at $z = 0.167$.

Finally, a comparison of the absorber at $z = 0.167$ and known high-redshift LLSs (Köhler et al. 1999; Lopez et al. 1999; Prochaska 1999; Prochaska & Burles 1999; Rauch, Sargent, & Barlow 1999) shows that all but one (Rauch et al. 1999) of these Lyman limit absorbers have similar estimates of the ionization parameter $U$. If the majority of LLSs continue to exhibit $log U \approx -2.5$ at all epochs, then it clearly begs the question whether these systems share similar physical properties such as gas temperature.

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