THE DETECTION OF TWO DISTINCT HIGH IONIZATION STATES IN A QSO LYMAN-LIMIT ABSORPTION SYSTEM: EVIDENCE FOR HIERARCHICAL GALAXY FORMATION AT z ~ 3?

DAVID KIRKMAN1 AND DAVID TYTLER1

Department of Physics and Center for Astrophysics and Space Sciences, University of California, San Diego, MS 0424, La Jolla, CA 92093-0424; dkirkman@ucsd.edu, tytler@ucsd.edu

Received 1998 August 28; accepted 1998 December 4; published 1999 January 25

ABSTRACT

We have detected two high ionization phases of gas in the z ~ 2.77 partial Lyman-limit system (LLS) toward QSO 1157+3143. We detect the first phase by C iv and Si iv absorption and the second phase—which is either warmer or undergoing larger random bulk motions than the first—via O vi absorption. Both phases of gas are present in similar column density ratios in each of the five velocity components, making it appear that this LLS is constructed of five very similar building blocks. We find that this system displays some of the properties expected of a hierarchical merging event, although published models may have trouble explaining the Si iv absorption we observe. When different ions show similar velocity structure, we commonly assume that they arise in the same gas, and we compare their column densities to derive the ionization and abundances. For this one absorption system, the different ions have similar velocity, but they do not arise in the same gas.

Subject headings: quasars: absorption lines—quasars: individual (1157+3143)

1. INTRODUCTION

Absorption systems with enough neutral hydrogen to be optically thick to Lyman continuum radiation are commonly found in the spectra of high-redshift QSOs. These Lyman-limit systems (LLSs) and damped Lyα (DLA) systems often show line absorption from multiple ionization states of several different elements, most commonly carbon and silicon. It is often assumed that optically thick absorption systems contain gas in two separate phases: gas that is shielded from UV background Lyman continuum radiation and thus contains low ions such as C ii and Si ii, and gas that is not completely shielded from the UV background and thus shows high-ionization species such as C iv and Si iv. The low ions are believed to be in a separate phase from the high ions because in DLA systems all low ions have a similar velocity structure that appears to have no relation to the velocity structure of the high ions, all of which also have a similar velocity structure (Prochaska & Wolfe 1997).

In recent years, many groups have begun to use numerical simulations to simulate the formation of structure in variants of cold dark matter (CDM) universes (Cen et al. 1994; Zhang, Anninos, & Norman 1995; Hernquist et al. 1996). These simulations naturally produce absorbers that at least superficially resemble LLSs and DLA systems as a natural result of the hierarchical structure formation that takes place in CDM models (Katz et al. 1996; Gardner et al. 1997). In most simulations, LLSs and DLA systems have very similar physical structures and tend to be protogalaxies in the process of formation via the merging of several smaller structures.

There is not complete agreement within the community that the structures identified in the CDM simulations accurately represent the absorbers seen in actual QSO spectra. In particular, Prochaska & Wolfe (1997) find that the kinematics of DLA low-ionization gas is consistent with the gas being located in a thick rotating disk—a picture that is quite different from the simulation results. Nonetheless, the advent of numerical simulations has sparked a renaissance in the study of QSO absorption systems, and the simulations are now making detailed predictions about the observed properties of absorption systems, including the metal lines in DLA systems and LLSs.

Rauch, Haehnelt, & Steinmetz (1997) calculated the expected metal absorption from DLA systems and LLSs found in a CDM simulation with the assumption that the absorbing gas had a uniform metallicity. They found that while the low ions are all found in the same gas, the gas producing most of the Si iv absorption is not the same gas producing C iv or O vi absorption. As expected, they found that absorption from low ions occurs in only the highest density gas near the center of the protogalactic structures. The high ions were found in lower density gas surrounding the protogalactic clump, in a structure resembling an onion. Si iv was found only very close to the center, much like the low ions. C iv was found primarily in low-density gas further out, and O vi was found mainly in even lower density gas further yet from the center of the clump. Si iv and C iv were found in gas inside the shock front of a collapsing object, whereas O vi was found in gas still falling into the structure. This resulted in O vi lines that were systematically wider than the C iv or Si iv lines.

In this Letter, we present the first multiple-component O vi absorption features to be detected in a high-z intervening absorption system. The only other O vi detection at high z (Kirkman & Tytler 1997) contained only one component, and only the O vi λ1032 line of the λ1032, 1039 doublet was detected because of blending. Here we report the detection of at least five O vi components in both members of the λ1032, 1039 doublet in the z ~ 2.77 LLS toward 1157+3143. We also see Si iv, C iv, C ii, Si ii, and Si iii. This system is remarkable because, as we will show, all high ions have a very similar velocity structure, yet we are able to show on observational grounds alone that the O vi absorption cannot all be occurring in the same gas that is producing the C iv and Si iv absorption.

2. THE z ~ 2.77 LLS

We observed QSO 1157+3143 for a total of 7 hr in 1996 March and 1997 January with the HIRES spectrograph (Vogt 1992) on the W. M. Keck Telescope during our search for
deuterium. The resulting spectrum has a resolution of 7.9 km s\(^{-1}\) and a signal-to-noise ratio of ~50 per 0.03 Å pixel. The spectrum was reduced and extracted in the standard fashion (e.g., Kirkman & Tytler 1997).

There are two LLSs in this spectrum, one at \(z \sim 2.94\) and another at \(z \sim 2.77\). The \(z \sim 2.94\) LLS in this spectrum shows neither O \(\text{v}\) nor C \(\text{iv}\) and will not be discussed. We do not have a good estimate of the H \(\text{i}\) column for the \(z \sim 2.77\) LLS because the \(z \sim 2.94\) LLS blots out the spectrum below 3600 Å, which prevents us from seeing any Lyman series line higher than Ly\(\gamma\). Nonetheless, we believe that the \(z \sim 2.77\) system is a Lyman limit because it shows both C \(\text{ii}\) and Si \(\text{ii}\), neither of which is expected to be present in an absorption system that is not optically thick to Lyman continuum radiation. The lines associated with the \(z \sim 2.77\) partial LLS found in this spectrum are shown in Figure 1.

Figure 2 shows the O \(\text{vi}\) and C \(\text{iv}\) lines of this system in more detail. We used VPFIT (Webb 1987) to fit Voigt profiles to the lines shown in Figure 2; the line parameters appear above each line in the figure. While fitting, we did not in any way tie line parameters between different elements—the O \(\text{vi}\) fit is completely independent of the C \(\text{iv}\) fit. Although there is not a one-to-one correspondence between the O \(\text{vi}\) and C \(\text{iv}\) lines in Figure 2, it is clear that the velocity structure of the O \(\text{vi}\) lines does trace the velocity structure of the C \(\text{iv}\) lines. Figure 2 also gives the impression that the O \(\text{vi}\) absorption is a smeared-out version of the C \(\text{iv}\) absorption. This impression is confirmed by noting that the \(b\) values are larger for O \(\text{vi}\) than for C \(\text{iv}\) for the absorbers centered near \(-140\) and \(40\) km s\(^{-1}\), which are well defined and lightly blended lines in all three species.

There is more than apparent similarity between the O \(\text{vi}\) and C \(\text{iv}\) lines in this absorption system. In Figure 3, we show that the O \(\text{vi}\) lines can be accurately fit using only profiles restricted to be at the same velocity as the identified C \(\text{iv}\) lines. While the velocities of the O \(\text{vi}\) lines in Figure 3 were fixed, the column densities and \(b\) values of each line were allowed to vary to produce the best match to the observed spectrum. Note that in the final fit, the \(b\) value in each O \(\text{vi}\) component is \(\sim 2\) times as large as in the corresponding C \(\text{iv}\) component and that the column density ratio \(N(\text{O vi})/N(\text{C iv})\) varies only by \(\sim 5\) between the different components.

### 3. Ionization State of the \(z \sim 2.77\) LLS

The ionization state of this system is not well constrained by the available data. This is because the O \(\text{vi}\) and C \(\text{iv}\) line widths in this system prevent us from using the commonly made assumption that all of the lines at the same velocity arise in the same gas. Thus, we cannot use the column density ratios of the observed ions to work out the ionization state of the system assuming either photoionization or collisional ionization equilibrium. As demonstrated in Figure 3, the O \(\text{vi}\) line is wider than the C \(\text{iv}\) line in each velocity component of this LLS. Since oxygen is heavier than carbon, this means that some or all of the O \(\text{vi}\) absorption is arising in gas different than that producing the C \(\text{iv}\) absorption—there are at least two phases of gas in this system. The phase that produces the O \(\text{vi}\) absorption is either warmer or more turbulent than the phase producing the C \(\text{iv}\) absorption.

All of the O \(\text{vi}\) lines associated with this system have \(b > 17\) km s\(^{-1}\), which is equivalent to \(T > 2.8 \times 10^5\) K if the line widths are thermal. An ionization parameter of \(U > 1\) is required for the UV lines associated with the \(z \sim 2.77\) LLS.
Fig. 2.—Independent Voigt profile fits to the O\textsc{vi} and C\textsc{iv} lines associated with the $z \approx 2.77$ LLS. The column density and velocity dispersion are displayed on top of each line.

4. DISCUSSION

There are several scenarios that can give rise to multiple high ionization phases of gas in an individual component of an absorption-line system. The absorbing gas may contain pockets of cool or warm (C\textsc{iv}, Si\textsc{iv}) gas intermixed with pockets of hot gas (O\textsc{vi}). In this scenario, a method must be found to widen the O\textsc{vi} lines; presumably they would arise in small pockets of shock-heated gas and/or expanding gas around collapsing substructure within each component (stars?). The similar metal column ratios imply the structure within each of the components is similar as well.

In a more likely scenario, the multiple phases are explained by density gradients in the absorbing components at each velocity. Moving along the gradient, the photoionization parameter of the gas will change, giving a large number of effective gas phases. As discussed in § 1, this sort of situation was produced in the simulations run by Rauch et al. 1997. In this scenario, the wide O\textsc{vi} lines are produced primarily because the O\textsc{vi}–absorbing gas is falling into the collapsing structure, whereas the C\textsc{iv}–absorbing gas is at rest behind the shock front. The observed wide O\textsc{vi} lines and the similar component structure of this LLS suggest that we may be observing the formation of a protogalaxy by the merging of several smaller structures. There is, however, at least one major difference between the data and the Rauch et al. simulation. In this system, the Si\textsc{iv} absorption is strong and has the same velocity structure as the other high ions. In the simulations, this will only occur if each velocity component is centered on the line of sight to the QSO because of the small effective cross section of Si\textsc{iv}–absorbing gas from the center of a collapsed object. This seems improbable. It will be interesting to see if the O\textsc{vi} lines observed at high resolution in other LLSs agree with the physical picture of the LLS suggested by these observations.

We thank Tom Bida and Barbara Schafer with the W. M. Keck Observatory for assistance with our observations of 1157+3143 and Tom Barlow for providing a copy of his extraction software, which allowed us to rapidly do science with our data. We thank Bob Carswell for making his VPFIT software package available to us. This work was supported in part by NSF grant 31217A and by NAGW-4497 from NASA.
Fig. 3.—Voigt profile fits to the O vi and C iv absorption with O vi components only at the position of C iv components identified in Fig. 2. With the exception of a small region near $v \sim 0$ km s$^{-1}$, all of the O vi absorption can be accurately fit. To produce an accurate fit, however, requires that $b_{OVI} > 2b_{CIV}$ in each component. We therefore conclude that while the O vi absorption closely traces the C iv absorption in velocity space, the O vi lines are systematically wider than the C iv lines.

REFERENCES

Cen, R., Miralda-Escude, J., Ostriker, J. P., & Rauch, M. 1994, ApJ, 437, L9
Donahue, M., & Shull, J. M. 1991, ApJ, 383, 511
Gardner, J. P., Katz, N., Hernquist, L., & Weinberg, D. H. 1997, ApJ, 484, 31
Hernquist, L., Katz, N., Weinberg, D. H., & Miralda-Escude, J. 1996, ApJ, 457, L5
Katz, N., Weinberg, D. H., Hernquist, L., & Miralda-Escude, J. 1996, ApJ, 457, L5
Kirkman, D., & Tytler, D. 1997, ApJ, 489, L123
Prochaska, J. X., & Wolfe, A. M. 1997, ApJ, 487, 73
Rauch, M., Haehnelt, M. G., & Steinmetz, M. 1997, ApJ, 481, 601
Webb, J. 1987, Ph.D. thesis, Univ. Cambridge
Vogt, S. S. 1992, in High-Resolution Spectroscopy with the VLT, ed. M.-H. Ulrich (ESO Conf. Proc. 40; Garching: ESO), 223
Zhang, Y., Anninos, P., & Norman, M. L. 1995, ApJ, 453, L57