Analysis of High Ions in Optically Thick Quasar Absorbers

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Abstract

Optically thick absorbers, a class of extragalactic gas clouds that includes damped Lyα absorbers and Lyman limit systems and appears in the absorption spectra of quasars, provide insight into the interactions of galaxies with the nearby intergalactic medium. The ionized metal species of C IV, Si IV, and O VI are of particular interest due to their ability to probe a wide temperature range of ionized gas within the galactic halo. Using QSO spectra from the High Resolution Echelle Spectrometer on the Keck 10 m telescope, a comprehensive search was undertaken for optically thick absorbers to supplement previous surveys, resulting in the largest sample of high ions in high redshift absorbers yet constructed. The velocity ranges and total column densities of these ions were measured and tabulated and a grading system implemented for OVI absorption. Preliminary analysis of the survey indicates a larger dispersion of total column densities and column density ratios, a larger average column density ratio of C IV to Si IV, and a smaller average column density ratio of C IV to O VI for high redshift absorbers than previously found in the Milky Way. Additionally, the presence of absorbers with O VI column density greater than $10^{15}$ cm$^{-2}$ suggests the presence of high redshift starburst galaxies, i.e. galaxies with over ten times more active star formation than the Milky Way.

Introduction

Galaxies are found to exhibit star formation throughout their evolution, requiring a constant influx of gas. The source of this influx is the intergalactic medium (IGM), a reservoir of gas encompassing the space between galaxies. The relationship between galaxies and the IGM is complex. Supernovae and the creation of new massive stars blow gas out of the galaxy into the IGM, enriching it with metals. Simultaneously, this enriched material is recycled back into the galaxy, fueling further star-formation. However, the outflow and accretion of gas and
their feedback effects on star formation are not well understood, especially at high redshifts of
$1.5 < z < 4$, representing a period of nine to twelve billion years ago when star formation rates in
galaxies were about 10 to 100 times greater than in the present universe.

One method of studying the Galaxy-IGM interface at high redshifts (high-z) is analyzing
absorption spectra of background quasars created by optically thick absorbers. These absorbers
are characterized by the large optical depth of their Ly$\alpha$ absorption line and are further
categorized by their neutral hydrogen column density ($N_{\text{HI}}$) into two groups: damped Ly$\alpha$
absorbers (DLAs), which have $\log(N_{\text{HI}}) \geq 20.3$, and Lyman limit systems (LLSs) with $16 < \log(N_{\text{HI}}) < 20.3$. DLAs and LLSs exhibit a multiphase structure, containing overlapping neutral,
weakly ionized, and strongly ionized gas, and have been found in previous studies to be
associated with galactic (and, in the case of DLAs, proto-galactic) halos (Lehner et al. 2009).

While the neutral component of DLAs and LLSs has been studied extensively, the
properties of their ionized component have not. The ionized gas could be especially important
for understanding galaxy-IGM interactions because the missing metals at high-z are likely in this
gas phase (Fox et al. 2007a,b), and because extent of different metal ions in the absorber have
been shown to be important to constrain the behavior of galactic outflow, accretion, and
feedback (Fox et al. 2007a,c, 2009, Lehner et al. 2008). Therefore, highly ionized metals or high
ions are the best way to probe ionized gas in DLAs and LLSs. The range of ionization energies
of high ions makes them effective indicators of the temperature and ionization mechanism of the
gas, important properties for understanding the behavior of DLAs and LLSs. The high ions
chosen for study in this survey are Si IV, C IV, and O VI. Si IV and C IV are ubiquitous in
DLAs and LLS and are generally uncontaminated because they are not in the Ly$\alpha$ forest, a term
used to describe the Ly$\alpha$ lines that contaminate the smaller wavelengths of spectra. O VI is in
the Lyα forest, making it more difficult to detect, but is of particular interest because its high ionization potential requires the mechanism of collisional ionization for its production (Si IV and C IV can both be photoionized) and its abundance can be used to calculate the amount of ionized hydrogen (H II) in the DLA or LLS because, unlike H I, H II cannot be directly observed.

The following study is a preliminary step in a larger attempt to comprehensively survey and characterize optically thick absorbers in order to better understand the behavior of gas in the IGM-galaxy interface at high redshift. Absorbers were systematically searched for in QSO spectra, the basic properties of the high ions Si IV, C IV, and O VI in these absorbers were measured, and basic analysis was conducted on the sample as a whole.

**Data Sample, Reduction, and Analysis**

The spectra used in this study come from observations made by the High Resolution Echelle Spectrometer (HIRES) at the Keck I 10-m Telescope, and retrieved from the Keck Observatory Archive at the NASA Exoplanet Science Institute. The high spectral resolutions (6-8 km/s) and signal-to-noise (S/N>20 with many S/N>50) of this sample mean highly reliable parameters can be estimated. The Keck/HIRES spectra cover wavelength ranges from 3000 to 10000 Å, but not continuously. At the redshifts of interest, the high ion doublet absorption lines of Si IV, C IV, and O VI found in the rich, ultraviolet section of the spectrum are shifted into the Keck/HIRES’s wavelength range, allowing for consistent coverage (see Table 1). Due to the high-z of the background QSO, contamination is a problem for a substantial part of the sample, since gas clouds along the line of sight to the QSO all leave absorption lines in the spectrum. This is especially a problem for detecting O VI, which is found within the Lyα forest.

The database includes 100 spectra, of which 71 were analyzed for this study, resulting in the identification of 211 high redshift absorbers, the largest such compilation of its kind. The
Table 1: High ion sample sizes

<table>
<thead>
<tr>
<th>Ion</th>
<th>$\lambda$ (Å)</th>
<th>$I.$ P. (eV)</th>
<th>$z_{\text{ground}}$</th>
<th>Sample Size</th>
<th>Samples with Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si IV</td>
<td>1393.8, 1402.8</td>
<td>33.5 – 45.1</td>
<td>1.2</td>
<td>204(105)</td>
<td>166(87)</td>
</tr>
<tr>
<td>C IV</td>
<td>1548.2, 1550.8</td>
<td>47.9 – 73.5</td>
<td>0.9</td>
<td>197(100)</td>
<td>168(82)</td>
</tr>
<tr>
<td>O VI</td>
<td>1031.9, 1037.6</td>
<td>113.9 – 138.1</td>
<td>1.9</td>
<td>145(62)</td>
<td>113(46)</td>
</tr>
</tbody>
</table>

Notes: $I.$P is the ionization potential range for the ion. $z_{\text{ground}}$ is the redshift above which lines can be seen from the ground at $>3000$ Å. Samples with errors excludes ions for which a lower or upper limit were estimated due to saturation or a non-detection respectively. Numbers in parentheses are the subset identified by the author.

The sample size of each ion is summarized in Table 1. The identification of absorbers within the quasar spectra was conducted using normalized spectra formatted by Professor John O’Meara. Professor O’Meara identified 106 of the absorbers by searching for DLAs and super LLSs ($\log[N_{\text{H}}] > 19$). This sample was supplemented by the author, who identified 105 absorbers by searching for strong Ly$\alpha$ absorption lines, the signature of strong H I absorbers such as a DLA or LLS. These absorbers were confirmed by over-plotting the high ion doublets to check for similar velocity profiles. In several cases, multiple DLAs or LLSs were identified within each spectrum. Despite the different sampling methods, no noticeable difference exists between the two samples.

For each absorption line, an IDL program was used to measure the parameters of velocity range (the velocities of ions within the absorber), total column density (the number of atoms of an ion per square centimeter within the absorber), and equivalent width (a measure of the strength of the absorption line). These values were measured via the apparent optical depth (AOD) method described by Savage and Sembach (Lehner et al. 2010). The AOD method requires fitting the continuum with a Legendre polynomial near the absorption lines of interest. In this study, a low degree polynomial (usually $<3$) was used because the spectra were already normalized over the entire observed wavelength range. This fit is critical for obtaining accurate measurements in the AOD method since changes in the continuum fit can substantially change the apparent optical depth (Lehner et al. 2010). Generally, a fit was found within 400 km/s of
the absorption line, but contamination sometimes required a larger velocity range to establish the continuum, possibly introducing non-negligible error into the measurements.

Following the fit of the continuum, the velocity range was identified by the minimum and maximum velocities to which the absorption line extended for each ion (the same velocity range was used for both doublets of each ion, but could be different among the ions). (To plot the spectra’s intensity as a function of velocity, the program set a zero point at the wavelength of the desired ion). To measure the total column density, the apparent column densities per unit velocity $N_a(v)$ of the absorption lines was measured via $N_a(v) = 3.768 \times 10^{14} \times \ln[1/F_{\text{obs}}(v)]/(f\lambda)$ cm$^{-2}$ (km/s)$^{-1}$, where $F_{\text{obs}}(v)$ is the normalized flux of the absorption line as a function of velocity and $f$ is the oscillator strength of absorption. Total column densities ($N$) were then obtained by integrating $N_a(v)$ over the velocity range specified. In cases of saturation where $F_{\text{obs}}(v)$ reaches zero, a lower limit value for was measured by the program, and in the absence of a detection, a 3σ upper limit was measured for $N$. Finally, the equivalent width of the line was measured by integrating the area of the absorption line over the velocity range.

These results were tabulated in files, which were then read by a program written by the author. The program recorded the velocity ranges and combined the total column density measurements for each ion to calculate a final value for $N$ using the following methodology:

- If $N_{\text{strong}}$ and $N_{\text{weak}}$ agreed, their average was calculated.
- If either $N_{\text{weak}}$ or $N_{\text{strong}}$ was an upper or lower limit or contained contamination, the other line’s column density was used exclusively.
- If both $N_{\text{weak}}$ and $N_{\text{strong}}$ were either upper or lower limits, the strong or weak line’s column density was used respectively.
• In the case of two contaminated lines, the less contaminated line’s column density was used and was appropriately flagged.

Subsequently, the total column density ratios between C IV and Si IV and C IV and O VI were calculated, ratios that could potentially trace the ionization mechanisms at the galaxy-IGM interface. No work has yet been done with the equivalent width measurements. In addition to the measurements, a grade was recorded for the quality of the O VI absorption lines on a scale of A – F, such that absorbers with uncontaminated lines and excellent agreement received an A.

**Preliminary Results**

The major aim of this survey was accumulating and organizing data in such a manner as to facilitate future analysis. Nevertheless, some preliminary efforts can be made to characterize the properties of the DLAs and LLSs, especially in comparing their properties to those measured in the Milky Way. The subsequent data for the Milky Way is taken from the sample of 29 extragalactic lines of sight found in Savage and Wakker 2009, a sample which excludes limits.

A first step is to compare the distribution of the total column densities of the high ions, the logarithms of which are plotted for the high-z absorbers in Figure 1. The distribution of all of the ions is logarithmic-normal and total column density increases as ionization energy increases, a trend that is mirrored in the Milky Way data. The most substantial difference between the two datasets is the size of the standard deviation for the DLAs and LLSs, which is double for C IV and O VI and almost triple for Si IV as compared to the Milky Way. Though the high-z sample is almost a degree of magnitude greater than the Milky Way sample, the difference is great enough to suggest a larger overall variation in column densities at high-z. Additionally, $N_{\text{mean}}$ is different in all three ions; Si IV’s mean is 0.30 less, C IV’s mean is 0.24 less, and O VI’s mean is 0.09 greater for DLAs and LLSs than for the Milky Way. Since O VI is
believed to trace hot ($\sim 10^5 - 10^6$ K), gas while Si IV and C IV are believed generally to trace
warm ($\sim 10^4$ K) gas, more hot gas appears to be present in high-z galaxies and their halos. This is
further supported if one considers that for many absorbers, $\log[\text{O VI}] > 14.8$. These high O VI
column densities are unseen in the Milky Way, but can be observed in local starburst galaxies at
least up to $\log[\text{O VI}] \sim 15$. The presence of such large $\text{O VI}$ values indicates a large amount of
hot gas, which is likely produced by strong feedback within the protogalaxies. Therefore,
protogalaxies can be far more active than local galaxies, with star formation rates that are over
10 times greater in order to produce such a large amount of hot ionized gas.

Another way of comparing optically thick absorbers and the Milky Way is their total
column density ionic ratios. This comparison is depicted in Figure 2, in which the logarithms of
the ratios $\text{N}_{\text{C IV}} / \text{N}_{\text{Si IV}}$ and $\text{N}_{\text{C IV}} / \text{N}_{\text{O VI}}$ are plotted, along with the mean values for the Milky
Way and the high-z absorbers, both with and without limits. The high-z absorbers have a lesser
mean value for $\log[\text{N}_{\text{C IV}} / \text{O VI}]$ (-0.52) and a greater mean value for $[\text{N}_{\text{C IV}} / \text{N}_{\text{Si IV}}]$ (0.83) as
compared to the Milky Way (-0.16 and 0.59), meaning DLAs and LLSs tend to have relatively more O VI and C IV than galaxies in the Milky Way, suggesting again the presence of more hot gas at high redshift in the galaxy-IGM interface.

A final preliminary analysis can be undertaken involving the velocity ranges of the high ions, which are shown in Figure 3. The line plotted on the graph is $y = x$, so the closer a point is to the line, the more similar the velocity ranges of the two ions. Most of the data are below the line for the $\delta v_{\text{Si IV}}$ versus $\delta v_{\text{C IV}}$ graph, implying that generally $\delta v_{\text{Si IV}} < \delta v_{\text{C IV}}$. When $\delta v_{\text{C IV}}$ is compared to $\delta v_{\text{O VI}}$, the data are more scattered, indicating that hot gas is observed over a larger velocity interval than cooler gas. It should be noted that the O VI sample likely includes absorbers that are contaminated by the Lyα forest, especially over large velocity intervals.

**Further Research**

This survey is a preliminary step in a larger research effort to gain a better understanding of the interactions of the IGM and galaxies at high-z. The most important result is the compilation of a comprehensive sample of DLAs and LLSs and an organized database of the...
properties of their key high ions. The sample includes a degree of magnitude more O VI lines than any other previous study, a notable accomplishment. Nevertheless, much work lies ahead. Over 25 percent of the QSO spectra need to be analyzed. N_{H I} measurements of the author’s sample need to be estimated to identify DLAs versus LLSs. Metallicities need to be measured to estimate the amount of ionized gas. Profile-fitting needs to be undertaken to determine the different phases and their properties in each DLA and LLS. Results need to be compared to theoretical models to constrain the ionization mechanisms. The work will require much more effort, but this survey is an essential first step.

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References