UNDERSTANDING PHYSICAL CONDITIONS IN HIGH-REDSHIFT GALAXIES THROUGH C I FINE STRUCTURE LINES: DATA AND METHODOLOGY

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ABSTRACT

We probe the physical conditions in high-redshift galaxies, specifically, the damped Lyα systems (DLAs) using neutral carbon (C i) fine structure lines and molecular hydrogen (H2). We report five new detections of C i and analyze the C i in an additional two DLAs with previously published data. We also present one new detection of H2 in a DLA. We present a new method of analysis that simultaneously constrains both the volume density and the temperature of the gas, as opposed to previous studies that a priori assumed a gas temperature. We use only the column density of C i measured in the fine structure states and the assumption of ionization equilibrium in order to constrain the physical conditions in the gas. We present a sample of 11 C i velocity components in six DLAs and compare their properties to those derived by the global C ii technique. The resulting median values for this sample are \( \langle n(H I) \rangle = 69 \text{ cm}^{-3} \), \( \langle T \rangle = 50 \text{ K} \), and \( \langle \log(P/k) \rangle = 3.86 \text{ cm}^{-3} \text{ K} \), with standard deviations, \( \sigma_{n(H I)} = 134 \text{ cm}^{-3} \), \( \sigma_{T} = 52 \text{ K} \), and \( \sigma_{\log(P/k)} = 3.68 \text{ cm}^{-3} \text{ K} \). This can be compared with the integrated median values for the same DLAs: \( \langle n(H I) \rangle = 2.8 \text{ cm}^{-3} \), \( \langle T \rangle = 139 \text{ K} \), and \( \langle \log(P/k) \rangle = 2.57 \text{ cm}^{-3} \text{ K} \), with standard deviations \( \sigma_{n(H I)} = 3.0 \text{ cm}^{-3} \), \( \sigma_{T} = 43 \text{ K} \), and \( \sigma_{\log(P/k)} = 0.22 \text{ cm}^{-3} \text{ K} \). Interestingly, the pressures measured in these high-redshift C i clouds are similar to those found in the Milky Way. We conclude that the C i gas is tracing a higher-density, higher-pressure region, possibly indicative of post-shock gas or a photodissociation region on the edge of a molecular cloud. We speculate that these clouds may be direct probes of the precursor sites of star formation in normal galaxies at high redshift.

Key words: galaxies: evolution -- intergalactic medium -- quasars: absorption lines

Online-only material: color figures

1. INTRODUCTION

The high-redshift neutral gas layers known as the damped Lyα systems (DLAs) are simultaneously well understood and mysterious. On the one hand, the large Sloan Digital Sky Survey (SDSS) survey has identified nearly 1000 DLAs and produced a statistically significant description of the H I column density distribution function, the line density, and the contribution to the neutral gas mass density of the universe, out to redshifts of \( z \sim 4 \) (Prochaska et al. 2005; Prochaska & Wolfe 2009). On the other hand, the precise nature of DLAs is still not well understood and basic physical properties such as the volume densities, temperatures, physical sizes, and masses are difficult to constrain due to the nature of their detection as absorption imprints on background quasar spectra.

As the dominant source of neutral gas in the universe between \( z = [0, 5] \), the DLAs represent a key link in the history of galaxy formation, as they likely provide the source of neutral gas to fuel star formation at high-\( z \) (Wolfe et al. 2003, hereafter WGP03). The purpose of this paper is to constrain the physical conditions in DLAs by taking advantage of a relatively simple three-level fine structure transition, the neutral carbon (C i) fine structure states, which are only 23.6 K and 62.4 K above the ground state, which makes them sensitive probes of conditions in cold gas. The advantage of using the fine structure states of C i is that rather than determining only a line-of-sight column density, the relative excitation of the C i fine structure states allows for a determination of local physical conditions such as volume density, temperature, and pressure.

For almost two decades, the utility of C i fine structure transitions in probing cold gas has been recognized and applied to the high-redshift universe. The C i fine structure levels are populated by collisional excitation and de-excitation, radiative decay, UV pumping, and direct excitation by the cosmic microwave background (CMB) radiation. Because of this sensitivity to the CMB, C i fine structure lines in DLAs were first used to determine the temperature of the CMB at high redshifts as a test of big bang cosmology (i.e., Songalia et al. 1994). However, because the ionization potential (IP) of neutral carbon is below a Rydberg (\( IP_{\text{C i}} = 11.3 \text{ eV} < IP_{\text{H i}} = 13.6 \text{ eV} \)), singly ionized carbon, C ii, is the dominant state of carbon in the interstellar medium (ISM), and C i is not commonly found in DLAs. Additionally, because the C i fine structure transitions are generally weak and suffer significant blending, it is only recently with modern high-resolution echelle spectrographs that detailed measurements of the lines have been possible.

C i has been detected in several high-\( z \) DLAs, often as a byproduct of a search for molecular hydrogen (H2), i.e., Srianand et al. (2005) and Noterdaeme et al. (2007a). Because they are photoionized and photodissociated, respectively, by photons of similar energy, the two species tend to be found together. Previous analyses of C i fine structure states in high-\( z \) DLAs have generally assumed a gas temperature in order to
calculate the gas volume density and have generally found that for reasonable assumptions of the gas temperature, C\textsc{i} detections require relatively high densities. In this paper, we introduce a technique in which we make no a priori assumptions about the gas temperature.

Inspired by the work of Jenkins & Shaya (1979) and Jenkins & Tripp (2001) who used C\textsc{i} fine structure absorption to probe pressures in the local Milky Way ISM, we implement their technique on high-redshift DLAs. Most recently, Jenkins & Tripp (2007) find that most of the C\textsc{i} in the Milky Way is in gas at pressures between 3 < \log(P/k) < 4 \text{ cm}^{-3}\text{ K}, with the distribution centered at \( P/k = 2700 \text{ cm}^{-3}\text{ K} \). We will show that, interestingly, our results for the high-redshift DLAs are similar to those of Jenkins & Tripp (2007) for the Milky Way ISM. In addition, by invoking the sensible assumption of ionization equilibrium, we can use the population of the C\textsc{i} fine structure levels to constrain the total radiation field in some cases. This in turn acts as a check on the radiation field as determined by the “C\textsc{ii}” technique” (WPG03; WGP03)—a way of measuring the radiation field due to star formation in a DLA by equating the cooling rate measured via the C\textsc{ii} fine structure transition with the heating rate.

This is the first in a series of two papers focused on deriving the physical conditions in DLAs via the analysis of C\textsc{i} fine structure lines. In this first paper, we report the detection of C\textsc{i} in five high-redshift DLAs, and analyze an additional two DLAs with previously published C\textsc{i} data. We derive limits on density, temperature, and pressure as well as the radiation field contained in the C\textsc{i}-bearing gas of each DLA. In the systems for which we have coverage of H\textsubscript{2}, we compare the C\textsc{i} detection technique on high-redshift DLAs. Most recently, Jenkins & Tripp (2001) who used C\textsc{i} analysis to the C\textsc{ii} populations. In the second paper of this series, we will extend our analysis to the C\textsc{i}-bearing DLAs already published in the literature, analyze the broader physical implications of the C\textsc{i} and finally, propose a physical picture of C\textsc{i}-bearing DLAs.

This paper is organized as follows. We discuss our data and data analysis techniques in Section 2. We present our procedure for analyzing the C\textsc{i} data through the specific example of DLA 0812+32 at \( z_{\text{abs}} = 2.626 \) in Section 3. We then summarize the results for each of the C\textsc{i}-bearing DLAs in Section 4. Section 5 contains discussion of the DLAs presented here and we conclude in Section 6. Throughout this paper, we make the standard assumption that the ratio of column density of element X is equal to the ratio of volume density \( \frac{N(X)}{N(Y)} = \frac{n(X)}{n(Y)}, \) i.e., we are analyzing average conditions along the line of sight.

2. DATA AND METHODOLOGY

The C\textsc{i} sample presented here represents serendipitous discoveries made during the course of an ongoing campaign to obtain high-resolution spectra of DLA targets for detailed study. Data for this paper were taken primarily with the HIRES spectrograph (Vogt et al. 1994) on the Keck I telescope, with a typical detector that resulted in an instrumental resolution FWHM = 6.25 km s\textsuperscript{−1}. Details of specific observations are given in Table 1. Data were reduced and continuum fit using the standard XIDL\textsuperscript{4} packages. Because of the complex blending of many close fine structure transitions that typically exhibit several velocity components, we were not able to successfully apply the apparent optical depth technique (Savage & Sembach 1991) for a measurement of the column densities. We also did not have the high signal-to-noise ratio (S/N) and resolution of the Jenkins & Tripp (2001) study of interstellar C\textsc{i}, in which they developed a modified apparent optical depth method (AODM) technique (Jenkins & Tripp 2001). Instead we used the VPFIT package, version 9.5\textsuperscript{5} to measure the C\textsc{i} fine structure column densities, \( N(C\textsc{i}), N(C\textsc{ii}^*) \), and \( N(C\textsc{ii}^{**}) \), redshifts, and Doppler parameters \( b \), where \( b = v/2\sigma \), and \( \sigma \) is the velocity dispersion in km s\textsuperscript{−1}. Wavelengths and \( f \)-values were taken from Morton (2003).\textsuperscript{6}

In general, we simultaneously fit as many C\textsc{i} multiplets as possible. In all cases, we included all multiplets that fell redward of the Ly\(\alpha \) forest, which generally included the strongest multiplets at 1656 Å and 1560 Å, and usually the multiplet at 1328 Å. In cases where a multiplet fell within the Ly\(\alpha \) forest, yet did not contain any obvious blending with a forest line, we included that multiplet in our analysis. We rejected sections of spectra that contained obvious blending.

To determine upper limits for non-detected fine structure states, generally for \( N(C\textsc{ii}^{**}) \), we used VPFIT, which allows for an estimation of the 1\(\sigma \) upper limit by inputting a “reasonable guess” of the column density and rerunning the fit to give linear errors. The error is then taken as the 1\(\sigma \) upper limit. For a conservative reasonable guess, we used the measured column density of the line with the smallest measured column density, usually \( N(C\textsc{ii}^*) \), since it is almost always the case that \( N(C\textsc{ii}^{**}) < N(C\textsc{ii}^*) \). This results in a conservative upper limit to the \( N(C\textsc{ii}^{**}) \) value.

We present one new detection of H\textsubscript{2} in DLA 2340–00, and we analyze the H\textsubscript{2} in DLA 0812+32. While it is likely that the other systems contain measurable H\textsubscript{2} as well, we lack the spectral coverage to confirm this speculation.

All other information about each DLA, including metallicity, dust-to-gas ratio, and log \( N(C\textsc{ii}) \) was determined using the AODM (Savage & Sembach 1991), unless otherwise stated (i.e., in the cases where we performed a full component analysis). To measure the log \( C\textsubscript{12}/C\textsubscript{18} \), we must employ the conventional method of measuring \( N(C\textsc{ii}) \) by proxy using \( N(\text{Si}\textsc{ii}) \), because the C\textsc{i} \( \lambda 1334 \) transition is saturated in every DLA presented in this paper. As in Wolfe et al. (2004), we let \( [C/\text{H}]^T = [\text{Si}\textsc{ii}/\text{H}] + [\text{Fe}/\text{Si}\textsc{int}] \), where \( [\text{Si}\textsc{ii}/\text{Si}\textsc{int}] = -0.2 \) for a minimal depletion model or \( [\text{Fe}/\text{Si}\textsc{int}] = 0.0 \) for a maximal depletion model. While Wolfe et al. (2004) estimate the error in the measurement of \( C\textsubscript{12}/C\textsubscript{18} \) to be 0.1 dex, we use the more conservative estimate of 0.2 dex.

Details of the observations are given in Table 1, while the details of the C\textsc{i} measurements are summarized in Table 2. In the following, we provide a brief summary of the data analysis of each DLA in our sample:

\( \text{DLA 0812+32, } z_{\text{abs}} = 2.62633. \) DLA 0812+32 at \( z_{\text{abs}} = 2.62633 \) has been studied extensively (see Prochaska et al. 2003), and boasts one of the highest known DLA metallicities and H\textsubscript{i} column densities. Prochaska et al. (2003) used the many available transitions to show that the relative elemental abundance pattern is similar to that of the Milky Way. Jorgenson et al. (2009) presented the first direct evidence of cold \( T_{\text{thermal}} \leq 78 \text{ K}, (115 \text{ K}, 2\sigma) \) gas at high redshift using a curve of growth analysis of a sub-resolution, narrow velocity C\textsc{i} component in

\textsuperscript{4} http://www.ucolick.org/~xavier/IDL/

\textsuperscript{5} http://www.ast.cam.ac.uk/~rfc/vpfit.html

\textsuperscript{6} Note, however, that there is some confusion over the correct \( f \)-values for the C\textsc{i} transitions given a more recent set determined by E. B. Jenkins (2006, private communication). Since we cannot determine which set of \( f \)-values is more correct, in this paper we use the Morton (2003) values to be consistent with what has previously been used in the literature.

\textsuperscript{7} The abundance ratio with respect to solar is defined as \( [X/Y] = \log (X/Y) - \log(X/Y)_{\odot} \).
this DLA, and recently, Tumlinson et al. (2010) presented the detection of HD.

In this work, we simultaneously fit data from three Keck HIRES runs with details given in Table 1. Eight multiplets were used to fit the C1 fine structure lines; λ1656, λ1560, λ1328, λ1280, λ1279, λ1277, λ1276, and λ1270. The λ1276–λ1280 multiplets were blended with a C1 IV doublet at $z_{abs} = 1.992$. Figure 1 contains the spectral data of DLA 0812+32, in black, overlaid with our fit, in red, and the C1 fine structure lines marked. Each velocity component is denoted by a different linestyle (solid, dashed, dotted, etc.) while each fine structure state is denoted by a different color (C1: red, C1*: green, C1**: blue). It is apparent from this figure that (1) in some cases the C1 fine structure transitions fall so close to each other that they are blended, and (2) the multi-component velocity structure found in most DLAs further complicates the analysis. As denoted in Figure 1, three C1 velocity components are required to fit this DLA. Component 1 at $z_{abs} = 2.625808$, or $v \sim -43$ km s$^{-1}$, with Doppler parameter of $b = 3.25$ km s$^{-1}$, is the weakest component and contains the largest errors. Component 2 at $z_{abs} = 2.6263247$ with $b = 2.57$ km s$^{-1}$, is located at $v = 0$ km s$^{-1}$, and has an upper limit on $N(C_1^{**})$. Component 3 at $v \sim +14$ km s$^{-1}$, or $z_{abs} = 2.626491$, is the narrow component reported in Jorgenson et al. (2009) with $b = 0.33$ km s$^{-1}$.
While the velocity structure of C\textsc{i} in DLA 0812+32 is well constrained by the fitting of many multiplets, our confidence in the fit is increased by the similar velocity structure seen in neutral chlorine, Cl\textsc{i}. Because of their similar IPs, both below a Rydberg, C\textsc{i} and Cl\textsc{i} are often observed to have the same velocity structure (Jura 1974a). This is seen in Figure 2 along with several other sub-Rydberg and low-ion transitions that trace the velocity structure of C\textsc{i}, namely, Ge\textsc{ii} \( \lambda 1237 \), Mg\textsc{i} \( \lambda 1827 \), Si\textsc{ii} \( \lambda 1845 \), and Zn\textsc{ii} \( \lambda 2062 \).

This DLA also contains relatively strong H\textsubscript{2}, with a total log \( N(\text{H}_2) = 19.90 \text{ cm}^{-2} \), giving a molecular fraction of \( f = 0.067 \), where \( f \) is defined as \( f = \frac{2N(\text{H}_2)}{N(\text{H}_1) + 2N(\text{H}_2)} \). The H\textsubscript{2} velocity components are consistent with those of C\textsc{i}.

**DLA 0812 + 32, \( z_{\text{abs}} = 2.066780 \)** Data for this DLA are the same as that for DLA 0812+32, \( z_{\text{abs}} = 2.62633 \) discussed above. There is one C\textsc{i} velocity component in this DLA. To fit C\textsc{i}, we used only the \( \lambda 1656 \) and \( \lambda 1560 \) multiplets because of heavy blending with the Ly\textalpha forest blueward of rest frame \( \sim \lambda 1467 \) Å, see Figure 3. This DLA also contains C\textsc{i}, however it is interesting to note that the centroid of the C\textsc{i} profile is displaced by \( \sim +5 \text{ km s}^{-1} \) with respect to \( v = 0 \text{ km s}^{-1} \) at the C\textsc{i} centroid of \( z_{\text{abs}} = 2.066780 \). While this is unexpected, it is also true of all of the low ions, see Figure 4. However, Si\textsc{i} and Mg\textsc{i} appear to align more closely with C\textsc{i}.

**DLA 1331 + 17.** Wolfe & Davis (1979) discovered 21 cm absorption toward QSO1331+17 at \( z_{\text{abs}} = 1.77642 \), a similar redshift at which a DLA had previously been discovered at optical wavelengths (Carswell et al. 1975). They deduced a spin temperature of \( T_s = 770-980 \text{ K} \) by combining the 21 cm line equivalent width with the \( N(\text{H}_1) \) obtained from Ly\textalpha absorption.

One of the first attempts to measure the CMB temperature at high redshift using C\textsc{i} was made by Meyer et al. (1986) using DLA 1331+17. They measured C\textsc{i} and put an upper limit on the ratio \( n(C^+)/n(C) \) that allowed them put an upper limit on the temperature of the CMB, \( T_{\text{CMB}} < 16 \text{ K} \) at \( z_{\text{abs}} = 1.776 \). Later, Songalia et al. (1994) used the Keck telescope to make more precise measurements. They succeeded in measuring the C\textsc{i} transition and derived a CMB temperature of \( T = 7.4 \text{ K} \) that agreed well with the theoretical prediction. More recently, Cui et al. (2005) discovered an unusually high level of molecular hydrogen (H\textsubscript{2}) in DLA 1331+17 using the Hubble Space Telescope. They detect a molecular fraction of \( 5.6\% \pm 0.7\% \) in a component at \( z_{\text{abs}} = 1.776553 \). They derive an excitation temperature of the H\textsubscript{2}-bearing component of \( T_{\text{ex}} = 152 \text{ K} \). Recently, Carswell et al. (2010) discovered a narrow velocity component of C\textsc{i} at \( z_{\text{abs}} = 1.776525 \) that requires gas with \( T_{\text{thermal}} \lesssim 218 \text{ K} \) (1σ).

To maximize the UV coverage for DLA 1331+17, we used a Keck HIRES spectrum with instrumental resolution FWHM = 6.25 km s\(^{-1}\) in combination with a bluer UVES spectrum of resolution FWHM = 7.0 km s\(^{-1}\) kindly provided by R. F. Carswell. This provided coverage of the maximum number of C\textsc{i} multiplets, down to the rest-frame C\textsc{i} \( \lambda 1277 \) multiplet at observed wavelength \( \lambda_{\text{obs}} \approx 3546 \) Å. We included in the fit the following multiplets: \( \lambda 1656, \lambda 1560, \lambda 1328, \lambda 1280, \) and \( \lambda 1277 \).

As shown in Figure 5, DLA 1331+17 requires three C\textsc{i} velocity components. Component 1, at \( v \approx 0 \text{ km s}^{-1} \), is the strongest component in terms of column density (see Table 2) with \( b = 5.08 \pm 0.24 \text{ km s}^{-1} \). Component 2, at \( v \approx 17 \text{ km s}^{-1} \), has a narrow velocity structure (\( b = 0.55 \pm 0.13 \text{ km s}^{-1} \)), and is discussed in detail in Carswell et al. (2010). The third component, at \( v \approx 20 \text{ km s}^{-1} \), with \( b = 24.45 \pm 6.2 \text{ km s}^{-1} \), does not exhibit measurable C\textsc{i} or C\textsc{i\textsuperscript{*}} absorbing. Lending confidence to the fit is the presence of C\textsc{i}, shown in Figure 6 along with several other sub-Rydberg and low-ion transitions that trace the velocity structure of C\textsc{i}, namely, P\textsc{ii} \( \lambda 1152 \), S\textsc{ii} \( \lambda 1250 \), Mn\textsc{ii} \( \lambda 2576 \), and Mg\textsc{i} \( \lambda 2852 \).

We can compare our results to another recent measurement of C\textsc{i} absorption in this system. Dessauges-Zavadsky et al. (2004) used Very Large Telescope (VLT) and Keck data to measure C\textsc{i} in two components, log \( N(C\textsc{i}) = 13.12 \pm 0.02 \text{ cm}^{-2} \) at \( z_{\text{abs}} = 1.776365 \) and log \( N(C\textsc{i}) = 12.72 \pm 0.02 \text{ cm}^{-2} \) at
Figure 2. DLA 0812+32 low ions. The blue vertical line at $v = 0$ km s$^{-1}$ marks component 2 at $z_{\text{abs}} = 2.6263247$, while the narrow Doppler parameter, cold component 3, is located at +14 km s$^{-1}$.

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

$z_{\text{abs}} = 1.776523$. While in the latter case, what we call component 2, their measurements agree with ours to within 1σ errors, component 1 is in disagreement, with small errors, by 0.12 dex. However, this difference is reasonable considering continuum placement uncertainties and the fact that they did not include fitting of the C$\text{I}$ fine structure states which involve considerable blending with the resonance line.

**Figure 3.** DLA 0812+32 $z_{\text{abs}} = 2.06$ C$\text{I}$ velocity structure. Notation is as in Figure 1. Only the 1656 Å and 1560 Å multiplets were used in the fit because of the serious blending with the Ly$\alpha$ forest in lower wavelength multiplets. The single C$\text{I}$ component is located at $v = 0$ km s$^{-1}$, with $z_{\text{abs}} = 2.066780$.

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

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**DLA 1755 + 578.** DLA 1755+578, at $z_{\text{abs}} = 1.9692$, contains eight C$\text{I}$ components, making it one of the more complex C$\text{I}$ systems. It is interesting in its own right because we have discovered the presence of Si$\text{II}^*$ absorption in this DLA. While Si$\text{II}^*$ has been observed in gamma-ray burst (GRB)-DLAs pumped by the UV radiation field of the GRB afterglow (Savaglio & Fall 2004; Prochaska et al. 2006), this is the first known case of Si$\text{II}^*$ observed in a high-redshift QSO-DLA. Because Si$\text{II}^*$ is generally thought to arise in warm gas—its excitation energy is 413 K—this system is not only unique but also extremely interesting since it appears that several velocity components contain both C$\text{I}$ and Si$\text{II}^*$ absorption, indicating that this is one of the rare DLAs exhibiting both cold neutral medium (CNM) and warm neutral medium (WNM) gas at high-$z$. We discuss this object in greater detail in a future paper.

**DLA 2100 − 06.** While this DLA, at $z_{\text{abs}} = 3.09237$, exhibits measurable C$\text{I}$, our data are not of sufficiently high quality to obtain good measurements of the C$\text{I}$ fine structure states. This is in part because the C$\text{I}$ lines are not strong, and in part because the strongest multiplet, $\lambda 1656$, falls close to an order gap and as a result is contained in a lower signal-to-noise region.

All C$\text{I}$ multiplets $\lambda 1277$ and redward are included in the fit. The fit requires three C$\text{I}$ velocity components, only one of which
**Figure 4.** DLA 0812+32 $z_{\text{abs}} = 2.066780$. Note the velocity offset between C\textsc{i} and the other low ions. Also note the blending of C\textsc{ii}$^*$. (A color version of this figure is available in the online journal.)

**Figure 5.** Spectral regions covering the five C\textsc{i} multiplets used in the analysis of DLA 1331+17. Notation is as in Figure 1. This system requires three C\textsc{i} components: component 1 at $v = 0$ km s$^{-1}$, or $z_{\text{abs}} = 1.77637$ is solid, component 2 at $v \sim 17$ km s$^{-1}$, or $z_{\text{abs}} = 1.77652$ is dashed, while component 3 at $v \sim 20$ km s$^{-1}$, or $z_{\text{abs}} = 1.77659$ is dotted. Interloper lines are denoted by dotted black lines. (A color version of this figure is available in the online journal.)
Figure 6. Resonance lines and low ions that trace the C i velocity structure of DLA 1331+17. $v = 0 \text{ km s}^{-1}$ located at component 1 at $z_{\text{abs}} = 1.77637$. Note that the C ii transitions are likely blended with a forest line due to its different velocity profile.

(A color version of this figure is available in the online journal.)
FINE STRUCTURE TO PROBE PHYSICAL CONDITIONS IN DLAs

3.1. The Steady State Equation

We developed an in-house code based on POPRATIO (Silva & Viegas 2001) to calculate the theoretical C i fine structure level populations by making the standard assumption of steady state. Following Silva & Viegas (2001), we considered spontaneous radiative decay, direct excitation by the CMB, UV pumping, and collisional excitation and de-excitation. As in POPRATIO, the rate equations leading to steady state populations of state \( i \) is given by

\[
\sum_j n_j \left( A_{ij} + B_{ij} u_{ij} + \Gamma_{ij} + \sum_k n_k q_{ij}^k \right)
\]

\[
= n_i \sum_j \left( A_{ij} + B_{ij} u_{ij} + \Gamma_{ij} + \sum_k n_k q_{ij}^k \right),
\]

where \( A_{ij} \) are the spontaneous decay transition probabilities, \( B_{ij} \) are the Einstein coefficients, \( u_{ij} \) is the spectral energy density of the radiation field, and \( \Gamma_{ij} \) is the indirect excitation rate due to fluorescence and is defined by Silva & Viegas (2001). The quantity \( n^k \) is the volume density of the collision partner \( k \), where \( k = (H^0, H^\pm) \) and \( q_{ij}^k = (\sigma v) \), is the collision rate coefficient. The reverse rates are calculated using the assumption of detailed balance. All coefficients were taken to be the same as those used in POPRATIO, with the exception of collisions with neutral hydrogen, for which we used the more recent rate coefficients calculated using the analytical formula by Abrahamsson et al. (2007) extended to the temperature range of \( T = 10,000 \) K. For the sake of simplicity, we did not consider excitation by collisions with either molecular hydrogen (\( H_2 \)) or helium (\( He^1 \)). In the case of the former, the paucity of \( H_2 \) found in DLAs, at typical fractions of less than \( \approx 10^{-5} \) renders the effect of collisions with \( H_2 \) so small as to be negligible. However, even in DLAs in which the \( H_2 \) fraction is relatively large (for DLA 1331+17, the molecular fraction was determined by Cui et al. (2005) to be \( f = 0.056 \) or \( 5.6% \pm 0.7% \)), \( H_2 \) does not have a large effect on the collisional excitation of C i. In the latter case of \( He^1 \), collision rates are significantly lower than those of other partners. Additionally, the density of \( He^1 \) compared with that of \( H^1 \) is typically \( n(He^1) = 0.0975 n(H^1) \) (Anders & Grevesse 1989), making collisions with \( He^1 \) relatively unimportant.

Direct excitation by the CMB is calculated assuming the standard cosmology and a CMB temperature of \( T = T_0(1+z) \) where \( T_0 = 2.725 \) K (Mather et al. 1999). At high redshift, the CMB radiation generally has the strongest effect on the C i fine structure level populations because of the small temperature difference between the ground and first fine structure states. However,
Figure 9. Spectra of DLA 2231−00 low ions. $v = 0$ km s$^{-1}$ is located on component 2 at $z_{\text{abs}} = 2.066122$ and marked by a vertical dashed blue line. Component 1 is located at $v \sim -77$ km s$^{-1}$.

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

Figure 10. J2340 C$\alpha$ velocity profiles over five multiplets, (a) 1656 Å, (b) 1560 Å, (c) 1328 Å, (d) 1280 Å, (e) 1277 Å. Notation is as in Figure 1. The components are labeled in (a), as 1–9 from lowest to highest relative redshift (relative to the arbitrarily chosen $v = 0$ km s$^{-1}$ at $z_{\text{abs}} = 2.054151$) and located at the following velocities: $v \sim 0$ km s$^{-1}$, 13 km s$^{-1}$, 37 km s$^{-1}$, 44 km s$^{-1}$, 52 km s$^{-1}$, 55 km s$^{-1}$, 57 km s$^{-1}$, 83 km s$^{-1}$, and 96 km s$^{-1}$.

(A color version of this figure is available in the online journal.)
depending on the physical circumstances, other mechanisms such as UV pumping or collisions can dominate.

We included UV pumping due to a radiation field consisting of two components that we will call $J_{\nu}^{\text{Bkd}}$, and $J_{\nu}^{\text{local}}$, and let $J_{\nu}^{\text{total}} = J_{\nu}^{\text{local}} + J_{\nu}^{\text{Bkd}}$. $J_{\nu}^{\text{Bkd}}$ is the background radiation due to the integrated contribution from high-$z$ galaxies and quasars, known as the Haardt–Madau background (Haardt & Madau 1996, and more recently using CUBA9). In all cases, the minimum value of the total radiation field is determined by $J_{\nu}^{\text{Bkd}}$. In each case, the value of $J_{\nu}^{\text{Bkd}}$ is calculated based on the redshift of the DLA, and these values are summarized in Table 4 later. For an explanation of these values, see Figure 1 of Wolfe et al. (2004). Because each C$\text{I}$-bearing DLA also contains strong C$\text{II}^{*} \lambda 1335.7$ absorption, we used the C$\text{II}^{*}$ technique (see WPGO3; Wolfe et al. 2004) to estimate the local radiation field due to star formation, $J_{\nu}^{\text{local}, \text{C}}$ and included this contribution in the UV pumping. The $J_{\nu}^{\text{local}, \text{C}}$ is calculated at $\lambda = 1500$ Å, or 8.27 eV, and in Section 5.1.2 we explain the estimated error on this value, $\sim \pm 20\%$. Note that in general, $J_{\nu}^{\text{local}, \text{C}} \neq J_{\nu}^{\text{local}}$. We introduce the notation $J_{\nu}^{\text{local}, \text{C}}$ to specify how the local radiation field is measured, i.e., in this case it is the local star formation rate per unit area measured via the C$\text{II}^{*}$ technique.

To quantitatively determine the effects of the radiation field on the C$\text{I}$ fine structure level populations, we plot the $n(\text{C}^{1+})/n(\text{C})$ and $n(\text{C}^{2+})/n(\text{C})$ versus neutral hydrogen density for excitation by a wide range of radiation fields in Figure 11. In this example, we have considered collisions with neutral hydrogen at $T = 100$ K, spontaneous radiative decay, and the excitation by the CMB at $z = 2$, in addition to a radiation field of varying strengths as denoted in Figure 11. At low density, excitation by the CMB is dominant, unless the input UV radiation field is strong, in which case, the UV dominates. At higher densities, i.e., $n(\text{H}) > 10^{10}$ cm$^{-3}$, collisional excitation becomes important and finally at $n(\text{H}) \lesssim 1000$ cm$^{-3}$ the levels thermalize. In other words, at low densities the CMB sets the floor of $n(\text{C}^{1+})/n(\text{C})$. Only when the radiation field exceeds a total strength of approximately $J_{\nu}^{\text{total}} \gtrsim 10^{-18.5}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$, the Haardt–Madau background alone at a redshift of $z \sim 2$, has essentially no effect on the C$\text{I}$ fine structure excitation.

3.2. Steady State Solution

The steady state densities in each of the C$\text{I}$ fine structure states are found by solving three homogeneous equations with three unknowns. To solve these three homogeneous equations, we solve for the ratio of each excited state relative to the ground state. We denote all terms involving CMB excitation, UV pumping, and collisions by the shorthand, $R_{ij} = B_{ij} \mu_{ij} + \Gamma_{ij} + \sum_{k} n^{k} q^{k}_{ij}$ which is summed over $k$ different collision partners, where all terms were defined in the previous subsection. Reverse reaction rates are calculated through the principle of detailed balance. Following Jenkins & Tripp 2001, see their Equations (10) and (11), we find

$$\frac{n(\text{C}^{1+})}{n(\text{C})} = \frac{(R_{01})(A_{2,0} + R_{2,1} + R_{2,0}) + (R_{02})(A_{2,1} + R_{2,1})}{(R_{12})(A_{2,0} + R_{2,0}) + (A_{1,0} + R_{1,0})(A_{2,1} + A_{2,0} + R_{2,1} + R_{2,0})}$$

and

$$\frac{n(\text{C}^{2+})}{n(\text{C})} = \frac{(R_{02})(A_{2,0} + R_{2,0}) + (R_{01})(R_{1,2})}{(R_{12})(A_{2,0} + R_{2,0}) + (A_{1,0} + R_{1,0})(A_{2,1} + A_{2,0} + R_{2,1} + R_{2,0})}$$

where the states C$\text{I}$, C$\text{II}$, and C$\text{III}$ are denoted by the indices 0, 1, and 2, respectively. The resulting theoretical solutions are functions of the density of neutral hydrogen, $n(\text{H})$, and the temperature. Following Jenkins & Shaya (1979) we define

$$f_{1} = \frac{n(\text{C}^{1+})}{n(\text{C})} = \frac{n(\text{C}^{1+})}{n(\text{C})}$$

and

$$f_{2} = \frac{n(\text{C}^{2+})}{n(\text{C})} = \frac{n(\text{C}^{2+})}{n(\text{C})}$$

where $n(\text{C})$ is the number density of neutral hydrogen, $n(\text{H})$, and $n(\text{C}^{1+})$, $n(\text{C}^{2+})$. We give the values of $(f_{1}, f_{2})$ for each component of each DLA in Table 2.

In Figure 12, we plot the theoretical solutions in the $(f_{1}, f_{2})$, plane for the example case of component 3 of DLA 0812+32. In this case, $J_{\nu}^{\text{local}, \text{C}}$ as derived from the C$\text{II}^{*}$ technique, is

Figure 11. Excitation of the fine structure level C$\text{I}^{*}$ (top) and C$\text{I}^{**}$ (bottom) caused by increasing the strength of the radiation field. We plot the ratio $n(\text{C}^{1+})/n(\text{C})$ and $n(\text{C}^{2+})/n(\text{C})$ and have included spontaneous radiative decay, excitation by the CMB at $z = 2$, and collisions with neutral hydrogen at a temperature of $T = 100$ K. HM is the value of the Haardt–Madau background at $z = 2$ and is therefore a minimum total radiation field. Note that the radiation field must be $\gtrsim 1 \times 10^{-18.5}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$ in order to cause significant effects to the level populations of the C$\text{I}$ fine structure states at low densities (i.e., when collisions are not the dominant mechanism).

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

9 CUBA (Haardt & Madau 2003) is available at http://pito.mib.infn.it/∼haardt/cosmology.html.
Figure 12. $f_1$ vs. $f_2$ for component 3 of DLA 0812+32, where $f_1 = n(C_{\text{ii}})/n(C_{\text{ii}})_{\text{tot}}$, $f_2 = n(C_{\text{ii}})/n(C_{\text{ii}})_{\text{tot}}$, and $n(C_{\text{ii}})_{\text{tot}} = n(C_{\text{ii}}) + n(C_{\text{ii}}^+) + n(C_{\text{ii}}^+)$. The data point is marked by a red asterisk and the 1σ error polygon is marked in red, while the 2σ error polygon is blue. Theoretical tracks are indicated by black points and run from $T = 10$–10,000 K and $n(\text{H}^1) = 10^{-5.5}$–$10^{4.1}$ cm$^{-3}$. For clarity, we have highlighted the tracks corresponding to $T = 10$, 100, and 1000 K in cyan.

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

Temperature, we determine $C_{\text{ii}}/C_{\text{tot}}$ for a range of possible electron densities, $n_e$ (details of the ionization equilibrium are given in WPG03, and we discuss the sensitivity to the radiation field in Section 3.3.1). We then use the measured $C_{\text{ii}}/C_{\text{tot}}$ of each DLA to constrain our allowed solutions. While we measure $N(\text{C})$ directly, we must employ the conventional method of measuring $N(\text{C}^\text{ii})$ by proxy using $N(\text{Si}^\text{ii})$, because the available $\text{C}^\text{ii}\lambda 1334$ transition is saturated in all the DLAs considered here. We generally measure the $\text{Si}^\text{ii}$ or $\text{S}^\text{ii}$ and $\text{Fe}^\text{ii}$ using the standard AODM, which is well suited for cases such as these in which we have more than one transition of an ion. As in Wolfe et al. (2004), we use $[\text{C}/\text{H}] = [\text{Si}/\text{H}] + [\text{Fe}/\text{Si}]_{\text{int}}$ where the intrinsic (nucleosynthetic) ratio $\text{[Fe}/\text{Si}]_{\text{int}} = -0.2$ for a minimal depletion model or $\text{[Fe}/\text{Si}]_{\text{int}} = 0.0$ for a maximal depletion model. We follow Murphy & Liske (2004) and adopt the minimal depletion model in this work, and analyze the implications of the minimal versus maximal depletion model in Section 5.1.1. While Wolfe et al. (2004) estimate the error in the measurement of $C_{\text{ii}}/C_{\text{tot}}$ to be 0.1 dex, we use the more conservative estimate of 0.2 dex. We also note that, assuming there is no hidden saturation of metals, this is the maximum $N(\text{C}^\text{ii})$ that could be associated with the $\text{C}^\text{ii}$ gas, and we discuss the implications of this assumption further in Section 5.1.3.

To demonstrate the constraints imposed by ionization equilibrium, in Figure 14 we plot the $\text{C}^\text{ii}$ solutions in terms of $n(\text{H}^1)$ versus $\log(C_{\text{ii}}/C_{\text{tot}})$ for the example case of component 3 in DLA 0812+32. The measured $\log(C_{\text{ii}}/C_{\text{tot}}) = 3.10$ is indicated by the red dashed line with a range of ±0.2 dex indicated by green dashed lines. It is obvious that the region of allowed $\text{C}^\text{ii}$ structure solutions is further constrained by invoking ionization equilibrium. For clarification, in Figure 15 we re-plot the density versus temperature diagram, however now we denote the final solutions, those constrained by the $C_{\text{ii}}/C_{\text{tot}}$ ratio, in black (1σ) and yellow (2σ). As a result, invoking ionization equilibrium results in even tighter constraints on the densities and temperatures of the $\text{C}^\text{ii}$-bearing cloud without making any assumptions about the gas temperature. In this example case, we constrain the density to be $72 \lesssim n(\text{H}^1) \lesssim 549$ cm$^{-3}$ while the temperature is constrained to be $25$ K $\lesssim T \lesssim 251$ K, and the pressure $3.54 \lesssim \log(P/k) \lesssim 4.80$ cm$^{-3}$ K. $\chi^2$ minimization finds the
and the assumption of ionization equilibrium.

The allowed radiation field utilizing only the C\textsc{i} results are in red while 2σ is in blue.

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

Figure 14. \(n(\text{H}i)\) vs. \(\frac{n(\text{C} \text{ii})}{n(\text{C} \text{i})}\) for the allowed solutions of DLA 0812+32 component 3. The measured \(n(\text{C} \text{ii})/n(\text{C} \text{i})\) is indicated by the red dashed line with green dashed lines indicating the errors of ±0.2 dex. 1σ results are in red while 2σ in blue.

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

Figure 15. \(n(\text{H}i)\) vs. temperature for the allowed solutions of DLA 0812+32 component 3. The final solutions, as constrained by \(C_{\text{II}}\), are shown in black (1σ) and yellow (2σ).

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

best-fitting solution: \(n(\text{H}i) = 100 \text{ cm}^{-3}\), \(T = 79 \text{ K}\), and \(\log(P/k) = 3.90 \text{ cm}^{-3} \text{ K}\).

3.3.1. Using Ionization Equilibrium to Constrain the Radiation Field

Until now we have assumed the UV radiation field due to star formation, \(J_{\text{local}}\), determined by the C\textsc{ii} technique. We will now relax this constraint and allow the input local radiation field to vary, repeat the above analysis for each case, and examine the results as a function of radiation field. We show that for some C\textsc{i}-bearing clouds we can place upper and lower limits on the allowed radiation field utilizing only the C\textsc{i} fine structure data and the assumption of ionization equilibrium.

We use a grid of \(J_{\text{local}}\) values from \(J_{\text{local}} \approx 10^{-21} - 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1}\). To differentiate these radiation fields from those predicted by the C\textsc{ii} technique, we will call them

\(J_{\text{local,C}i}\). For each \(J_{\text{local,C}i}\), we first add the \(J^\text{Bl}d\) to obtain a \(J_{\text{local,C}i}^{\text{total}}\), and then rerun the above analysis, calculating the 1σ versus 2σ tracks for each \(J_{\text{local,C}i}^{\text{total}}\), followed by the ionization equilibrium analysis.

In Figure 16, we plot the 1σ C\textsc{i} results for the example case of DLA 1331+17 on a graph of \(C_{\text{II}}\) versus \(n(\text{H}i)\) where for clarity we show only a sub-sample of the entire \(J_{\text{local,C}i}^{\text{total}}\) grid results. Solutions corresponding to each \(J_{\text{local,C}i}^{\text{total}}\) are represented by different colors. Again, we use the \(C_{\text{II}}/C_{\text{I}}\) data to constrain the allowed solutions, and it is apparent that for \(J_{\text{local,C}i}^{\text{total}} \gtrsim 1 \times 10^{-19} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1}\), there are no acceptable solutions. This limit on \(J_{\text{local,C}i}^{\text{total}}\) is actually quite strict considering that the Haardt–Madau background is only \(\sim 1\) order of magnitude lower than this value.

This technique places an upper limit on the local radiation field, and hence the star formation rate, using only C\textsc{i} fine structure absorption and the assumption of ionization equilibrium, without invoking any assumptions about star formation from the C\textsc{ii} technique. We note in this example, of DLA 1331+17, component 3, that the strength of the radiation field as determined by the C\textsc{ii} technique \((J_{\text{local,C}i}^{\text{total,C}i} = 3.3 \times 10^{-19} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1})\) is just slightly higher than the 1σ upper limit derived independently from the C\textsc{i} data. However, in the case of DLA 1331+17, the C\textsc{ii} transition is likely blended with a Ly\(\alpha\) forest line, forcing us to estimate the true \(N(\text{C} \text{ii})\) by assuming it traces the velocity structure of other low ions and fitting it together with the forest line as explained in Section 4.3.

A byproduct of this analysis places limits on the density, temperature, and pressure of the cloud. In this example case of DLA 1331+17, at the 1σ level the density is limited to the range, \(n(\text{H}i) \lesssim 44 \text{ cm}^{-3}\) while the temperature is constrained to be \(79 \lesssim T \lesssim 794 \text{ K}\,\) and the pressure \(3.50 \lesssim \log(P/k) \lesssim 4.04 \text{ cm}^{-3} \text{ K}\). Again, we stress that these limits are derived independently of the results of the C\textsc{ii} technique, using
4. RESULTS

A summary of the details of each DLA is presented in Tables 2–6. Table 2 provides a summary of the C I data, Table 3 provides a summary of general DLA information, Table 4 gives the resultant radiation fields derived from the C I technique, and in Table 5 we show the final C I fine structure solutions giving allowed ranges of densities, temperatures, and pressures. Finally, in Table 6, we give the results of lifting the C I constraint on the local radiation field.

We now briefly describe the results for each C I-bearing DLA. The casual reader may wish to skip directly to the more general discussion of the results in Section 5.

4.1. FJ0812+32,  \( z_{\mathrm{abs}} = 2.62633 \)

This DLA contains three distinct C I velocity components whose C I fine structure levels we will analyze individually. In measuring the metallicity, \( N(\text{C} \text{ I}) \) and \( N(\text{C} \text{ I}^+) \) we will take two approaches: the first, discussed here, and the second, the individual component analysis, discussed in Section 4.1.1. Heavy blending of line profiles and the uncertainty/degeneracy of line profile fitting techniques have led to the customary use of the AODM technique to measure the amount of metals over the entire, blended DLA profile. Additionally, this avoids any question about the distribution of the N(H I), which by definition is damped and therefore kinematically unknowable. Because we are measuring the metals over the entire (blended) DLA, we refer to these measurements as “global,” and we apply them to each C I component, which we consider reasonable given that the low ions such as S II and Si II track the velocity components of C I, see Figure 2.

We measure \( N(\text{C} \text{ I}^+) = 14.30 \pm 0.01 \text{ cm}^{-2} \) which along with the C I technique determines that the radiation due to stars \( J_{\text{local,C} \text{ I}^+} = 7.17 \times 10^{-19} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1} \). Adding in the contribution from the background, \( J_{\text{tot,C} \text{ I}^+} = 2.45 \times 10^{-20} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1} \), gives \( J_{\text{tot,C} \text{ I}^+} \sim 4.7 \times 10^{-19} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1} \). The excitation rates due to the local star formation alone are \( \Gamma_{01} = 3.17 \times 10^{-2} \text{ s}^{-1} \), \( \Gamma_{02} = 2.40 \times 10^{-9} \text{ s}^{-1} \), and \( \Gamma_{12} = 3.12 \times 10^{-9} \text{ s}^{-1} \). These can be compared with those of the Haardt–Madau background at the redshift of this DLA that produces excitation rates \( \Gamma_{01} = 1.09 \times 10^{-10} \text{ s}^{-1} \), \( \Gamma_{02} = 8.23 \times 10^{-11} \text{ s}^{-1} \), and \( \Gamma_{12} = 1.07 \times 10^{-10} \text{ s}^{-1} \). We used the total radiation field and the assumption of ionization equilibrium to determine solutions for the three C I components that are labeled 0812+32 global in Table 5. We are unable to perform an analysis of component 2 given that the upper limit of \( N(\text{C} \text{ I}^+) \leq 12.39 \text{ cm}^{-2} \) is relatively large, resulting in a (f 1, f 2) combination with no limitation on \( n \) and \( T \).

We can use the constraints on the volume density to estimate the physical size of the cloud. Using the neutral hydrogen column density \( N(\text{H} \text{ I}) = 21.35 \text{ cm}^{-2} \) and, for example, the best-fit volume density for component 3, \( n(\text{H} \text{ I}) \approx 100 \text{ cm}^{-3} \), we can estimate the size of the C I-bearing cloud to be \( \ell = N(\text{H} \text{ I})/n(\text{H} \text{ I}) \approx 2.24 \times 10^{19} \text{ cm} \), or \( \approx 7 \text{ pc} \). This estimation is technically an upper limit to the size of the cloud that assumes that all of the H I is associated with the C I component.
When we relax the constraint of \( J_{\nu}^{\text{total}, C\,^{1+}} \) as derived from \( N(\text{C}^{+}) \), as discussed in the previous section, at the 2\( \sigma \) level we constrain the density to \( n \geq 0.1 \text{ cm}^{-3} \) and \( n \geq 7 \text{ cm}^{-3} \) for components 1 and 3, respectively. In both cases, we place a not-so-stringent upper limit on the allowed radiation field of \( J_{\nu}^{\text{total}} \leq 773 \times 10^{10} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1} \).

### 4.1.1. DLA 0812+32: Individual Component Analysis

While the initial modeling was completed using the radiation field and metallicity as measured over the entire profile, it is clear upon careful inspection of the spectrum (see Figures 2 and 7 of Jorgenson et al. 2009), that the depletion, and hence, dust-to-gas ratio, is not constant over the three components. This motivates our attempt to analyze each velocity component individually. Specifically, component 3, the narrow component, contains obvious \( \zeta(Fe)\, C\,^{1+} \), and \( C\,^{1+} \), while it exhibits no evidence for \( Cr\,^{3+} \). A natural explanation is that \( Cr\,^{3+} \) is heavily depleted onto dust grains in component 3. However, as discussed in Jorgenson et al. 2009, blending precludes a straightforward measurement of the equivalent width, and profile fitting using VPFIT, produces a \( Zn\,^{2+} \) column density in component 3 that is unrealistically high and ruled out by an upper limit on
$$N(\text{O} \equiv)$$ assuming solar relative abundances. We explain this by assuming the presence of another weak, broad component (for details, see Jorgenson et al. 2009), and model the log $$N(\text{Zn} \equiv)$$ in component 3.

Because Zn $$\equiv$$ and Cr $$\equiv$$ are not saturated and appear to trace the velocity structure of C1 quite well, we use these ions to determine the metal distribution, the dust-to-gas ratio, and the $$N(\text{C} \equiv)$$ in each component separately. To do this, we first tie the redshifts and $$b$$-values of each ion together and then use VPFIT to determine the column densities in each component. It is expected that Zn $$\equiv$$ and Cr $$\equiv$$ be tied together because they are metal-line transitions arising in singly ionized species with similar IPs, and thus are likely to show the same physical/velocity structure. However, they will not necessarily exactly trace the C1, given that C1 is affected by the incident $$J_{\text{total}}$$ and $$n_e$$, and if there is a gradient in $$J_{\text{total}}$$ or $$n_e$$, this could cause a difference between the structure of C1 and the other low ions. We give the results of this fitting in Table 7. In light of the work of Jorgenson et al. (2009), we include an additional broad weak component, in order to achieve a realistic $$N(\text{Zn} \equiv)$$ in component 3.

Due to the nature of damped lines, we cannot use Ly$$\alpha$$ to determine the distribution of the neutral hydrogen among these components. Therefore, we assume that the $$N(\text{H})$$ traces the low-ion metals, in this case Zn $$\equiv$$, and that the neutral hydrogen is distributed proportionally to the metals. This results in each component having the same metallicity, $$[\text{Zn}/\text{H}] = -0.58$$. We note, that in theory, this metallicity should be the same as that determined for the global case, $$[\text{Zn}/\text{H}] = -0.81$$. However, the individual component analysis reveals the presence of the narrow component 3, for which we have estimated the $$N(\text{Zn} \equiv)$$ based upon an upper limit on $$N(\text{O} \equiv)$$. While the exact metallicity of this component remains a mystery without higher resolution data, it is apparent that component 3 lacks significant Cr $$\equiv$$, indicating a high level of depletion, and consequently a higher dust-to-gas ratio than components 1 and 2. Following WPG03 (their Equation (7)), we define the dust-to-gas ratio relative to the Milky Way as follows

$$\kappa = 10^{[\text{Zn}/\text{H}]_{\text{int}}} (10^{[\text{Cr}/\text{Zn}]_{\text{int}}} - 10^{[\text{Cr}/\text{Zn}]_{\text{gas}}}),$$

where “gas” is the abundance ratio in the gas phase and “int” is the intrinsic nucleosynthetic abundance. We calculate the dust-to-gas ratio in component 3 to be ~17% of the Milky Way (log $$\kappa = -0.78$$. For comparison, Prochaska et al. (2003) measure $$\kappa \approx 6$$% (log $$\kappa = -1.24$$) over the entire profile of this DLA, and the typical dust-to-gas ratio in DLAs is ~1/3 solar. We summarize information about each component in Table 7.

As we might expect, given that the column densities of all low ions with the exception of Cr$$^\ast$$, but including Cr$$^\ast$$, are much higher in component 3 (due to the fixed small Doppler parameter), the $$J_{\text{local},\text{C}1}$$ of component 3 deduced from the Cr$$^\ast$$ technique is more than 1 order of magnitude larger than that determined for components 1 and 2. The results of the C1 models for each component are presented in Table 5 where they are denoted by the subscript “div.” Note that the radiation field for component 3 predicted by the C1$$^\ast$$ technique is quite large, at 260 x 10$$^{-19}$$ erg cm$$^{-2}$$ s$$^{-1}$$ Hz$$^{-1}$$ sr$$^{-1}$$. The solutions require low temperatures ($$T \lesssim 32$$ K) and densities in excess of 10$$^3$$ cm$$^{-3}$$, which imply an upper limit on the cloud size of $$\ell \lesssim 0.1$$ pc. This small size may be in conflict with the evidence against partial covering provided by the H$_{2}$, see Section 4.1.2. It is possible that we have overestimated the amount of N(Cr$$^\ast$$) associated with the narrow component 3, and that more of the N(Cr$$^\ast$$) is associated with the broader component 4, but we would require a higher resolution spectrum to confirm this scenario.

Relaxing the constraint of $$J_{v}$$ local determined by the Cr$$^\ast$$ technique, gives no limits on temperature, and a large range of allowed densities for component 1 ($$n(\text{H}) = 0.002-4166$$ cm$$^{-3}$$), with a lower limit of $$n(\text{H}) \gtrsim 6$$ cm$$^{-3}$$ for component 3.
Constraints on the allowed radiation fields are consistent with that determined by the C\textsuperscript{II} technique.

4.1.2. DLA 0812+32 Molecular Hydrogen

This DLA also shows evidence of relatively strong molecular hydrogen (H\textsubscript{2}), see Figure 17. As shown in Jorgenson et al. (2009), there is no evidence for partial coverage, as the H\textsubscript{2} lines are black at line center. We used VPFIT to fit the H\textsubscript{2}, which required three components whose redshifts roughly agree with those of the three C\textsuperscript{I} components. While the Doppler parameters do not agree with those of the C\textsuperscript{I}—they are roughly similar to or smaller, whereas we would expect them to be larger by a factor of (6)\textsuperscript{2}—we will refer to these H\textsubscript{2} components as components 1, 2, and 3, and assume that they are co-spatial with the C\textsuperscript{I} components. This is not the first report of such differences in the $b$-values between H\textsubscript{2} and C\textsuperscript{I} components in DLAs (Noterdaeme et al. 2007a, 2007b). Because of the close match in redshift space and the likelihood that C\textsuperscript{I} and H\textsubscript{2} are co-spatial, we fixed the well-determined Doppler parameter of component 3 to that of the C\textsuperscript{I} ($b_{C1} = 0.33 \pm 0.05$ km s\textsuperscript{-1}), scaled by the relative atomic weights as done in Jorgenson et al. (2009).\textsuperscript{10} We list the parameters of the H\textsubscript{2} fits in Table 8.

It is interesting to note that like the C\textsuperscript{I}, the majority of the H\textsubscript{2} resides in component 3, the narrow velocity component. The fraction of H\textsubscript{2} in component 3, $f \geq 0.06$, or $\geq 6\%$, with the upper limit representing the uncertainty in $N$(H\textsubscript{I}) distribution, is among the highest found in DLAs. While we have tied the Doppler parameter to that of the C\textsuperscript{I}, we note that because of heavy saturation of the $J=0$ and $J=1$ lines in this component, log $N$ is determined by the damping wings of the profile and is therefore insensitive to the choice of $b$. We have verified this by artificially fixing the Doppler parameter to a range of values from $b = 0.2$–6 km s\textsuperscript{-1} as well as by raising the continuum by 5\%. None of these tests change the resultant $N$(H\textsubscript{2}, $J=0$) and $N$(H\textsubscript{2}, $J=1$) by more than $\sim$0.03 dex. While the $J=0$ and $J=1$ lines are completely insensitive to the Doppler parameter, the higher level $J$ states are sensitive to the choice of Doppler parameter. Therefore, we also report a model in which we have allowed the Doppler parameter of component 3 to be determined by the $J=3$ state and we report the results, called model 2, in Table 8.

We can estimate the kinetic temperature of the clouds using the column densities of H\textsubscript{2} in the $J=0$ and $J=1$ rotational states and assuming the states are thermalized according to the Boltzmann distribution (see Equation (8) in Levshakov et al. 2002). The excitation temperature, $T_{\text{ex}}$, is defined by

$$T_{\text{ex}} = \frac{N(J)}{N(0)} \frac{g(J)}{g(0)} \exp \left[ - \frac{B_J(J+1)}{T_{\text{ex}}} \right],$$  \hspace{1cm} (7)

where $B_J = 85.36$ K for the vibrational ground state and $g(J)$ is the degeneracy of level $J$. In Figure 18, we show the standard H\textsubscript{2} excitation diagram, log($N$/g) versus energy, for the $J=0$ to $J=5$ levels for each component. As explained in the Appendix (on molecular hydrogen), the kinetic temperature of the gas is proportional to the negative inverse of the slope determined by the $J=0$ and $J=1$ levels, assuming that the levels are

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|c|c|}
\hline
Attribute & Comp. 1 & Comp. 2 & Comp. 3 & Comp. 4 \\
\hline
$N$(Cr\textsubscript{III}) (cm\textsuperscript{-2}) & 12.91 ± 0.04 & 13.15 ± 0.02 & $\leq 11.71$ (1σ) & 12.52 ± 0.07 \\
$N$(Zn\textsubscript{III}) (cm\textsuperscript{-2}) & 12.44 ± 0.04 & 12.96 ± 0.02 & 13.00\% & 12.32 ± 0.24 \\
$N$(C\textsubscript{II}) (cm\textsuperscript{-2}) & 13.56 ± 0.2 & 13.69 ± 0.01 & 15.14 ± 0.17 & 13.08 ± 0.05 \\
$N$(H\textsubscript{2}) (cm\textsuperscript{-2}) & 20.41 & 20.93 & 20.97 & 20.29 \\
$[\text{Zn/H}]$ & −0.58 ± 0.04 & −0.58 ± 0.02 & −0.58 & −0.58 ± 0.24 \\
$[\text{Cr/H}]$ & −1.13 ± 0.04 & −1.41 ± 0.02 & ≤ −2.89 & −1.40 ± 0.07 \\
$[\text{Cr/Zn}]$ & −0.55 ± 0.06 & −0.83 ± 0.03 & ≤ −2.31 & −0.82 ± 0.12 \\
$\kappa$ & 0.09 & 0.13 & 0.16 & 0.13 \\
$log_{10}k$ & −1.04 & −0.90 & −0.78 & −0.90 \\
$C_{\text{Hz}}$ & 3.71 ± 0.2 & 3.56 ± 0.2 & 3.06 ± 0.2 & ... \\
$t_{\text{H2}}$ & 26.37 & 26.76 & 25.35 & 26.73 \\
$j_{\text{rot}} / 10^{19}$ & 19.2 & 6.3 & 259.9 & 2.5 \\
$b_{\text{H2}}$ & $2.34 \times 10^{-5}$ & $9.0 \times 10^{-3}$ & 0.14 & ... \\
$b_{0}$ (s\textsuperscript{-1}) & $3.53 \times 10^{-11}$ & $6.74 \times 10^{-14}$ & $1.53 \times 10^{-14}$ & ... \\
$b_{1}$ (s\textsuperscript{-1}) & $5.97 \times 10^{-11}$ & $8.96 \times 10^{-14}$ & ... & ... \\
$S_{\text{H2}}$ & 0.08 & 3.6 × 10\textsuperscript{-4} & 3.9 × 10\textsuperscript{-5} & ... \\
$S_{\text{H2}}$ & 0.98 & 0.91 & 0.88 & ... \\
$v_{\text{rot}}$ (K) & 0.08 & $3.3 \times 10^{-4}$ & $3.41 \times 10^{-5}$ & ... \\
$n(\text{H1})/10^{19}$ & 0.37 & 0.17 & 0.36 & ... \\
$n(\text{H2})/10^{20}$ (cm\textsuperscript{-3}) & 21 & 11 & 37 & ... \\
\hline
\end{tabular}
\caption{Dust-to-Gas Ratio Component Analysis of DLA 0812+32}
\end{table}

\textsuperscript{10} $b_{\text{H2}} = (6)^{1/2} b_{C1} = 0.81$ km s\textsuperscript{-1}. 

Notes.

\footnotesize
\begin{itemize}
\item \textsuperscript{a} Doppler parameter fixed to match that of C\textsuperscript{I} as determined by Jorgenson et al. (2009).
\item \textsuperscript{b} $N$(Zn\textsubscript{III}) fixed by upper limit on $N$(O\textsubscript{I}) assuming solar relative abundances. See the text for details.
\item \textsuperscript{c} Summed over the two components required by VPFIT, as explained in the text.
\item \textsuperscript{d} $N$(H\textsubscript{I}) scaled to trace $N$(Zn\textsubscript{III}).
\item \textsuperscript{e} Dust-to-gas ratio relative to Milky Way, as defined in the text.
\item \textsuperscript{f} erg cm\textsuperscript{-2} s\textsuperscript{-1} Hz\textsuperscript{-1} sr\textsuperscript{-1}.
\item \textsuperscript{g} Density derived from the H\textsubscript{2} as explained in the text.
\end{itemize}
Using the $J$ fields for components 1, 2, and 3, respectively:

- The $J$ larger, or smaller in the case of component 2, than the field. Also notice that these radiation fields are only slightly thermalized (a good assumption given the densities of these clouds), i.e., $T_{\text{ex}}$ equals the kinetic temperature. For components 1, 2, and 3, we determine the following temperatures, $T_{\text{ex}} = 102\, \text{K}$, $T_{\text{ex}}^{10} = 73\, \text{K}$, and $T_{\text{ex}}^{01} = 47\, \text{K}$, respectively. These are consistent with the temperatures derived from the $\text{C}\,\text{i}$ data, which leads us to believe there is good correspondence between the $\text{C}\,\text{i}$ and $\text{H}_2$ data and that the gas probed here is a CNM. Also, the $T_{\text{ex}}^{01} = 47\, \text{K}$ derived for the narrow component 3 is consistent with the upper limit on the thermal temperature of $T_{\text{thermal}} \leq 78\, \text{K}$ required by the curve of growth determined Doppler parameter.

We can also use the $\text{H}_2$ data to determine the ambient incident radiation (UV flux) field on the cloud, $J_{\nu,\text{total}}^{\text{H}_2}$, using the $J = 0$ and $J = 4$ states (see the Appendix for details). The level populations above $J = 1$ are unlikely to be thermalized since their larger Einstein $A$ coefficients imply that these states are depopulated by spontaneous emission more rapidly than by collisional de-excitation; this rules out the condition of detailed balance required to establish thermal equilibrium. Instead, these states are likely to be populated by UV pumping, which is what we shall assume. Following Hirashita & Ferrara (2005), we call this radiation field $J_{\nu,\text{W}}^{\text{L}}$, as determined by absorption in the Lyman–Werner $\text{H}_2$ bands. Since the $\text{H}_2$ measurement should reflect the total incident radiation field, $J_{\nu,\text{local}}^{\text{I}} + J_{\nu,\text{bkd}}^{\text{I}} = J_{\nu,\text{W}}^{\text{L}} = J_{\nu,\text{total}}^{\text{H}_2}$. Results for the photoabsorption rate, $\beta$, and for the shielding terms, both self-shielding by $\text{H}_2$ and shielding due to dust, are given in Table 7. Note that $\beta_0$ is derived from the $J = 4$ population, while $\beta_1$ is derived from the $J = 5$ population. Using the $J = 4$ population, we obtained the following radiation fields for components 1, 2, and 3, respectively: $J_{\nu,\text{total}}^{\text{H}_2} = <3.7 \times 10^{-20}, 1.7 \times 10^{-20}$, and $3.6 \times 10^{-20}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$. Note, that for component 1, $N(\text{H}_2, J = 4)$ is an upper limit, and hence, this is technically an upper limit on the radiation field. Also notice that these radiation fields are only slightly larger, or smaller in the case of component 2, than $J_{\nu,\text{bkd}}^{\text{I}}$. This places a rather strict limit on additional radiation from local star formation.

Interestingly, the radiation field as calculated from the $\text{H}_2$ is rather independent of the choice of global versus individual component parameters. In the above, we gave the results of the individual component analysis, where we assumed that the $N(\text{H}\,\text{i})$ tracks the metals, in this case the $N(\text{Zn}\,\text{ii})$, and used the individual component metallicity, $N(\text{H}\,\text{i})$ and dust-to-gas ratio to calculate the radiation field. If we instead use the “global” model, the $N(\text{H}\,\text{i})$ increases to the global value, here $N(\text{H}\,\text{i}) = 21.35\, \text{cm}^{-2}$, while $\kappa$ decreases in each component to the global value, here $\kappa = 0.07$. These two effects essentially cancel each other out in the calculation of shielding (see Equation (A13) in the Appendix) and we obtain very similar radiation fields in each case (i.e., for component 1, $J_{\nu,\text{total}}^{\text{H}_2} < 4.2 \times 10^{-20}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$, compared with $J_{\nu,\text{total}}^{\text{H}_2} < 3.7 \times 10^{-20}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$).

We do not understand why the radiation field derived from the $\text{H}_2$ data is $\approx 20$ times smaller than that derived by the $\text{C}\,\text{ii}$ technique, $J_{\nu,\text{total}}^{\text{H}_2} = 7.4 \times 10^{-19}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$. Additionally, the radiation field predicted by the $\text{H}_2$ levels for component 2 is low enough that it is excluded by the $\text{C}\,\text{i}$ data and the Haardt–Madau background (however, we note that the difference is not large and it could be within the errors—i.e., for component 2, if we consider the errors on the $J = 0$ and $J = 4$ levels we derive $J_{\nu,\text{total}}^{\text{H}_2} = 3.1 \times 10^{-20}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$, consistent with the Haardt–Madau background, but still $\approx 20$ times smaller than the $\text{C}\,\text{ii}$ prediction). This conflict could potentially be resolved if either (1) we are underestimating the population in the $N(\text{H}_2, J = 4)$ level—which could be caused by hidden saturation of narrow components as was demonstrated for the narrow component in DLA 1331+17 (Carswell et al. 2010), where the $N(\text{H}_2, J = 4)$ is likely underestimated because of the presence of the small Doppler component which contains the majority of the molecular gas (see further discussion in Section 4.3 and Carswell et al. 2010), or (2) the $\text{C}\,\text{ii}$ prediction is overestimating the radiation field. In the latter case, the radiation field is dependent upon the assumption of the equilibrium...
pressure existing at the geometric mean (see Section 5.1.1 for details). If instead the equilibrium pressure is located at $P_{\text{min}}$ or $P_{\text{max}}$, the resultant radiation field can change by up to a factor of 10 (for example, see Table 12). In the former case, we estimate that if the radiation field as predicted by the C1 technique is accurate and the H2 feels this entire radiation field, we require the amount of H2 in the J = 4 level to increase by a factor of $20$, to $N(\text{H}_2, J = 4) \sim 15.3 \, \text{cm}^{-3}$. This large amount of H2 is ruled out by the data unless it exists in a very narrow component with $b \lesssim 0.2 \, \text{km s}^{-1}$.

We also derive densities from the H2 data (see the Appendix), assuming the temperature is equal to the kinetic temperature derived from the $J = 0$ and $J = 1$ states. The resultant densities, $n(\text{H}_2) = 21, 11, \text{and } 37 \, \text{cm}^{-3}$ for components 1, 2, and 3, respectively, are nearly consistent with the C1 results (where for components 1 and 3 we derived $n(\text{H}_2) = 23–417 \, \text{cm}^{-3}$ and $72–549 \, \text{cm}^{-3}$, respectively). Again, since the radiation fields were not consistent and they are involved in this calculation, we may expect some of the discrepancy. We note, however, that the densities are consistent with the lower limits derived from the C1 data alone ($n(\text{H}_2) \geq 0.1$ and $\geq 7 \, \text{cm}^{-3}$, respectively).

Additionally, we can use the J = 2 rotational state to place an upper limit on the density if the excitation temperature, $T_{\text{ex}}$, is not equal to that of $T_{\text{ex}}^{01}$, indicating that the J = 2 state is

### Table 8

| Component 1 | Ion | $\sigma_{f b}$ | $\sigma_{b a}$ | $b$ (km s$^{-1}$) | $\sigma_{b}$ | $\log N$ (cm$^{-2}$) | $\sigma_{\log N}$ | $T_{\text{ex}}$ (K) |
|-------------|-----|---------------|---------------|-----------------|-----------|---------------------|-------------------|-----------------|
| H2J0        | 2.625812 | 0.000011    | 1.03         | 0.11           | 15.03    | 0.15                | ...               | 102 $\pm$ 1     |
| H2J1        | ...    | ...          | ...          | ...            | 15.26    | 0.15                | 132 $\pm$ 6      | 150 $\pm$ 2     |
| H2J2        | ...    | ...          | ...          | ...            | 14.04    | 0.06                | ...               | 222 $\pm$ 9     |
| H2J3        | ...    | ...          | ...          | ...            | 13.39    | 0.10                | 257 $\pm$ 25     | ...             |
| H2J4        | ...    | ...          | ...          | ...            | <12.64   | ...                 | ...               | ...             |
| H2J5        | ...    | ...          | ...          | ...            | 12.22    | 0.61                | 257 $\pm$ 25     | ...             |

| Total $N(\text{H}_2)$ = | 3.01 $\times$ 10$^{15}$  |
| log($\log N(\text{H}_2)$) = | 15.48  |
| $f^b$ | $\geq$ 2.69 $\times$ 10$^{-6}$  |

| Component 2 | Ion | $\sigma_{f b}$ | $\sigma_{b a}$ | $b$ (km s$^{-1}$) | $\sigma_{b}$ | $\log N$ (cm$^{-2}$) | $\sigma_{\log N}$ | $T_{\text{ex}}$ (K) |
|-------------|-----|---------------|---------------|-----------------|-----------|---------------------|-------------------|-----------------|
| H2J0        | 2.626326 | 0.000001    | 2.67         | 0.09           | <18.45c   | ...                 | ...               | ...             |
| H2J1        | ...    | ...          | ...          | ...            | 18.25    | 0.04                | >64               | ...             |
| H2J2        | ...    | ...          | ...          | ...            | 15.49    | 0.06                | >61               | ...             |
| H2J3        | ...    | ...          | ...          | ...            | 14.43    | 0.01                | >83               | ...             |
| H2J4        | ...    | ...          | ...          | ...            | 13.18    | 0.10                | >119              | ...             |
| H2J5        | ...    | ...          | ...          | ...            | <12.60   | ...                 | >151              | ...             |

| Total $N(\text{H}_2)$ < | 4.61 $\times$ 10$^{18}$  |
| log($\log N(\text{H}_2)$) < | 18.66  |
| $f^b$ | $\geq$ 4.1 $\times$ 10$^{-3}$  |

| Component 3, model 1 | Ion | $\sigma_{f b}$ | $\sigma_{b a}$ | $b$ (km s$^{-1}$) | $\sigma_{b}$ | $\log N$ (cm$^{-2}$) | $\sigma_{\log N}$ | $T_{\text{ex}}$ (K) |
|----------------------|-----|---------------|---------------|-----------------|-----------|---------------------|-------------------|-----------------|
| H2J0                | 2.626491 | 0.000001    | 0.81d         | ...            | 19.79    | 0.03                | ...               | ...             |
| H2J1                | ...    | ...          | ...          | ...            | 19.15    | 0.03                | 47 $\pm$ 1       | ...             |
| H2J2                | ...    | ...          | ...          | ...            | 16.60    | 0.03                | 57 $\pm$ 1       | ...             |
| H2J3                | ...    | ...          | ...          | ...            | 15.11    | 0.05                | 74 $\pm$ 1       | ...             |
| H2J4                | ...    | ...          | ...          | ...            | 13.99    | 0.04                | 110 $\pm$ 1      | ...             |

| Total $N(\text{H}_2)$ = | 7.58 $\times$ 10$^{19}$  |
| log($\log N(\text{H}_2)$) = | 19.88  |
| $f^b$ | $\geq$ 0.06  |

| Component 3, model 2 | Ion | $\sigma_{f b}$ | $\sigma_{b a}$ | $b$ (km s$^{-1}$) | $\sigma_{b}$ | $\log N$ (cm$^{-2}$) | $\sigma_{\log N}$ | $T_{\text{ex}}$ (K) |
|----------------------|-----|---------------|---------------|-----------------|-----------|---------------------|-------------------|-----------------|
| H2J0                | 2.626494 | 0.000001    | 1.19e         | ...            | 19.81    | 0.03                | ...               | ...             |
| H2J1                | ...    | ...          | ...          | ...            | 19.13    | 0.03                | 45 $\pm$ 1       | ...             |
| H2J2                | ...    | ...          | ...          | ...            | 16.21    | 0.11                | 52 $\pm$ 2       | ...             |
| H2J3                | ...    | ...          | ...          | ...            | 14.88    | 0.07                | 71 $\pm$ 1       | ...             |
| H2J4                | ...    | ...          | ...          | ...            | 13.97    | 0.04                | 109 $\pm$ 1      | ...             |

| total $N(\text{H}_2)$ = | 7.81 $\times$ 10$^{19}$  |
| log($\log N(\text{H}_2)$) = | 19.89  |
| $f^b$ | $\geq$ 0.07  |

**Notes.**

- Excitation temperature between rotational level $J$ and $J = 0$.
- Molecular fraction $f$ calculated using $N(\text{H}_2)_{\text{total}} = 21.35 \, \text{cm}^{-2}$, so that these values are technically lower limits.
- We report the 2σ upper limit because blending with the stronger $J = 0$ line of component 3 makes the formal errors large.
- Model 1: Doppler parameter tied to that of C1. Note that the $J = 0$ and $J = 1$ transitions are heavily saturated and therefore the resultant log $N$ is determined by the damping wings and is insensitive to the choice of $b$.
- Model 2: Doppler parameter determined by the $J = 3$ state.
not thermalized, and that the density is below $n_{\text{crit}}$, the critical density needed for thermalization. We plot critical density as a function of temperature for the $\text{H}_2$ $J$ states in Figure 19. In component 1 of DLA 0812+32, $T_{\text{ex}}^1 = 132$ K is greater than $T_{01} = 102$ K, indicating that the density must be less than $n_{\text{crit}}$. In this case, we derive a upper limit on the density of component 1 of DLA 0812+32, $n_{\text{crit}} \lesssim 10^3$ cm$^{-3}$. For component 2, $T_{02} = 47$ K is slightly less than $T_{01}$—indicating either that it is thermalized, or that this is within the errors. In either case, the upper limit derived from the next higher state, $T_{03}$, would not be that restrictive as $n_{\text{crit}} \sim 10^3$ cm$^{-3}$.

### 4.2. FJ0812+32, $z_{\text{abs}} = 2.066780$

The $\text{C} \text{n}^+$ transition of this DLA falls in the Ly$\alpha$ forest, and because the profile is quite different from that of the other low ions (see Figure 4), it is difficult to make a definitive estimate of the true $\text{C} \text{n}^+$ column density. Instead, we attempt to estimate the star formation rate by assuming three models motivated by the bimodality of DLA cooling rates (Wolfe et al. 2008). In the first case, case (a), we assume this is a “low-cool” DLA and use the average low-cool $\ell_c = 10^{-27.4}$ erg s$^{-1}$ H$^{-1}$. This assumption is likely the closest to the truth given that several physical traits of this DLA match those of the low-cool population of DLAs, i.e., the small value of the low-ion velocity, $\Delta v = 26$ km s$^{-1}$ is more likely to be drawn from the low-cool sample, with median $\Delta v = 46$ km s$^{-1}$, than from the high-cool sample with median $\Delta v = 104$ km s$^{-1}$. The $\text{Si} \text{n} \ 1526$ rest-frame equivalent width is also small at, $W_{1526} = 0.22 \pm 0.01$, compared with the low-cool median $W_{1526} = 0.26 \pm 0.09$, while the metallicity, $[\text{M}/\text{H}] = -1.38 \pm 0.01$, is slightly higher than the median metallicity for the low-cool population $[\text{M}/\text{H}] = -1.74 \pm 0.19$. This discrepancy in metallicity may simply be the result of metallicity increasing with decreasing redshift, as the $z_{\text{abs}} = 2.06$ of this DLA is lower than the median $z_{\text{abs}} = 2.85$ of the $\ell_c$ sample (Wolfe et al. 2008). Finally, the dust-to-gas ratio $\log_{10} \kappa = -2.74$ is similar to the median low-cool dust-to-gas ratio, $\log_{10} \kappa = -2.57 \pm 0.17$. In the second case, case (b), we will again make the low-cool assumption, but instead of the standard $\alpha$-enhancement assumption of $[\text{Fe}/\text{Si}] = -0.2$, we will assume $[\text{Fe}/\text{Si}] = 0$. Finally, in the last model, case (c), we will assume that the DLAs are a “high-cool” DLA and has an $\ell_c$ equal to the median high-cool DLA $\ell_c = 10^{-26.6}$ erg s$^{-1}$ H$^{-1}$.

We present the results for the three cases in Table 5. It is clear from the resultant densities that either cases (a) or (b) are more likely to be correct. In case (c), there are no acceptable $1\sigma$ solutions, and the range of densities at the $2\sigma$ level ($n(\text{H}1) > 3800$ cm$^{-3}$) seems unphysical. Densities this high are unlikely to be observed because they imply a very small cloud size that would be unlikely to cover the background quasar, i.e., here, the cloud size is estimated as $\ell \lesssim N(\text{H}1)/n(\text{H}1) \lesssim 10^{21.5}/3800 = 8.3 \times 10^{17}$ cm $\lesssim 0.3$ pc.

Following our assumption that the minimal depletion model is more likely to be correct, we conclude that case (a) is the best physical approximation for this system. If we now relax the constraint imposed by the $\text{C} \text{n}^+$ technique, and model a range of possible $J_{\nu}^{\text{total}}$, we find that at the $2\sigma$ level, we can restrict the density to $n \gtrsim 32$ cm$^{-3}$, $T \lesssim 1585$ K, and $J_{\nu}^{\text{total}} = 0.41–195 \times 10^{-19}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$, see Table 6.

### 4.3. DLA 1331+17

Here, we discuss the analysis of component 1, at $z_{\text{abs}} = 1.77636$, the only component with all three $\text{C} \text{i}$ fine structure lines detected. The Haardt–Madau background at the redshift...
of this DLA is given by $J_{\text{Bld}} = 2.53 \times 10^{-20} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1}$. To estimate the local stellar contribution to the UV field, we utilize the C ii transition. While WPG03 report log $N$(C ii) $= 14.05 \pm 0.05$ cm$^{-2}$ for this object, the C ii transition is likely blended with a Lyα forest line because its velocity profile is very different from that of the low ions, see Figure 6. Generally, the C ii velocity profile traces that of low ions such as Si ii and Al0800. Therefore, we cannot exclude the possibility that the C ii transition is blended with a forest line, and we take the WPG03 value of log $N$(C i) $= 14.05 \pm 0.05$ cm$^{-2}$ as an upper limit. To obtain an estimate of the actual N(C ii), assuming that it is blended, we (R. F. Carswell 2007, private communication) fixed the shape of the velocity profile to that of Si ii and normalized the C ii contribution by fitting the profile simultaneously with a coincident Lyα line. Summing over the C ii components results in an estimate of the true N(C ii) of log $N$(C ii) $\leq 13.56$ cm$^{-2}$. With this value of C ii absorption, the C ii technique results in a star formation rate that produces a radiation field of $J_{\text{Bld}} = 3.1 \times 10^{-19}$ erg cm$^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1}$. Therefore, the total input radiation field, that is, $J_{\text{local}} + J_{\text{Bld}}$, is $J_{\text{total}} = 3.3 \times 10^{-19}$ erg cm$^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1}$. Finally, the C i fine structure data constrained by ionization equilibrium, give $2\sigma$ results of 16 $\leq T \leq 32$ K, 91 $\leq n(H) \leq 363$ cm$^{-3}$, and 3.36 cm$^{-3}$K $\leq \log(P/k) \leq 3.86$ cm$^{-3}$K.

We can compare our results to those of Cui et al. (2005), who used CLOUDY to derive a best-fit model to their H2 data that resulted in a hydrogen number density $n(H_2) \approx 0.2$ cm$^{-3}$ and $T \approx 140$ K for the H2-bearing cloud at $z_{\text{abs}} = 1.776553$. This cloud is clearly not in pressure equilibrium with the C i cloud of our analysis, component 1 at $z_{\text{abs}} = 1.77637$, i.e., while the temperature is somewhat higher, the density is more than 2 orders of magnitude lower, resulting in pressures of $P/k \approx 28$ cm$^{-3}$K for the H2-bearing cloud. The C i-bearing cloud more closely resembles the C i-bearing clouds in the local ISM as found by Jenkins & Tripp (2007) and Jenkins & Tripp (2001). We discuss these similarities further in Section 5.3.

Cui et al. (2005) determine a photoabsorption rate based on the population of H2 in the J = 0 and J = 4 states, the latter of which is optically thin and therefore measures the intensity of radiation outside the cloud. Solving for this radiation field they derive $J_{\nu} (\lambda = 1000 \text{ Å}) = 2.1 \times 10^{-3} J_{\nu} (\lambda = 1000 \text{ Å})$, where $J_{\nu} (\lambda = 1000 \text{ Å})$ is the UV intensity in the solar neighborhood at 1000 Å and is, according to their paper, equal to $J_{\nu} (\lambda = 1000 \text{ Å}) = 3.2 \times 10^{-20}$ erg cm$^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1}$. They do recognize that the radiation field as determined by the H2 J states is $\sim 3$ orders of magnitude weaker than that determined by the C ii technique and comment that this is a discrepancy. More importantly, however, this radiation field is $\sim 3$ orders of magnitude below the Haardt–Madau background, which sets a lower limit to the radiation field. It is difficult to understand at first why the molecular hydrogen excitation is not consistent with this minimum radiation field. A solution exists however, if the bulk of the H2 gas resides in the narrow C i velocity component, i.e., component 2, and hence, has been missed because of the effects of hidden saturation. Carswell et al. (2010) have completed an analysis of this narrow component and include a detailed interpretation of the H2 data that is consistent with both the Haardt–Madau background and the local stellar field derived by C ii.

When we relax the constraint on the radiation field as determined by the C ii technique and allow the field to vary, as already discussed in Section 3.3.1, we can constrain the radiation field to $J_{\text{total}} \leq 1 \times 10^{-19}$ erg cm$^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1} \ (1\sigma)$.

This limit on $J_{\text{total}}$ is actually quite strong considering that the Haardt–Madau background is only $\sim 1$ order of magnitude lower than this value. Note that the lower limit on the allowed $J_{\text{total}}$ is fixed by $J_{\text{Bld}}$. It is apparent from Figure 16 that the density is limited to the range, $11 \leq n(H) \leq 44$ cm$^{-3}$ while the temperature is constrained to be $79 \text{ K} \leq T \leq 794 \text{ K}$, and the pressure $3.5 \leq \log(P/k) \leq 4.04$ cm$^{-3}$K. We stress that these limits are derived independent of the results of the C ii technique, using only the C i fine structure data and the assumption of ionization equilibrium for a range of possible radiation fields. The $2\sigma$ results provide the less restrictive results $J_{\text{total}} \leq 8.6 \times 10^{-18}$ erg cm$^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1}$, $n(H) \leq 10$ cm$^{-3}$, and $T \leq 794 \text{ K}$.

### 4.4. J2100–00

While insufficiently good quality data hinder a full analysis of DLA 2100–00, we attempted an analysis of component 1, by treating the upper limit on $N$(C i) as a detection. The measured $N$(C ii) produces a $J_{\text{local}} = 17 \times 10^{-19}$ erg cm$^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1}$, also an upper limit. The relatively large errors on the fine structure column densities do not produce very restrictive results. However, the VPFFIT derived Doppler parameter of this component, $b = 0.2 \pm 0.3$ km s$^{-1}$, if real, places a strict upper limit on gas temperature of $T_{\text{thermal}} \leq 29$ K, which is consistent with the results from the C i fine structure analysis. Unfortunately, the weakness of the C i line coupled with the low S/N of the data, makes a curve of growth analysis inconclusive. For the purposes of this paper however, it is the C i column densities that are important, and while they typically depend on the choice of Doppler parameter, we can obtain a sort of lower limit to the column density by fixing a relatively large Doppler parameter, i.e., $b = 7$ km s$^{-1}$. We measure $N$(C i) $= 12.12$ cm$^{-2}$, which is well within the errors quoted in Table 2, and see that in this case, the C i column densities have little dependence on changes in $b$.

### 4.5. Q2231–00

While there are two C i components contained in the DLA at $z_{\text{abs}} = 2.066$, here we will focus only on component 2, which possess measurable C i fine structure lines. While not formally an upper limit, the detection of $N$(C i) is relatively weak and has large error. For the purpose of this analysis, we will treat this value as a detection.

We estimate the $J_{\text{local}}$ from the measured $N$(C i) with some confidence, even though it falls within the Lyα forest, because the velocity profile of C ii closely traces that of other low ions as expected. Using this $J_{\text{local}} \approx 24.7 \times 10^{-19}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$, we find 199 cm$^{-3}$ $\leq n \leq 1513$ cm$^{-3}$, and $13 \leq T \leq 25$ K, see Table 5. Relaxing the constraint of $J_{\text{local}}$ given by the C ii technique results in a lower limit on the density of $n(H) \geq 3$ cm$^{-3} \ (2\sigma)$.

### 4.6. J2340–00

DLA 2340–00 is a relatively complex system requiring nine C i velocity components. Given the strong blending of transitions and the resultant uncertainty on upper limits, we do not analyze those components for which $N$(C i) is not detected, namely, components 1 and 7. In addition, the column densities of component 6 have extremely large errors, making analysis pointless, as well as the unphysical condition of $N$(C i) $> N$(C i).

This DLA contains a relatively high total column density of molecular hydrogen, log $N$(H2) $= 18.20$ cm$^{-2}$, or $f = 0.014$. 

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The neutral hydrogen column density, at log N(Hi) = 20.35 ± 0.15 cm−2, is close to the threshold defining a DLA (log N(Hi) = 20.30 cm−2), which supports the findings of Noterdaeme et al. (2008) that the probability of detecting H2 does not strongly depend on N(Hi). Furthermore, the low-ion velocity profile is large, with Δ v = 104 km s−1, and the cooling rate, as determined by Cii* over the entire profile, at log ξe = −26.15 erg s−1 H−1, is among the highest of DLAs. Because of the complex nature of the Cii, the H2, and the low-ion profiles, all requiring multiple components, and because of heavy blending and saturation in some components of the low ions, we were not able to obtain unique fits to all low-ion components using VPFIT. Instead, we analyzed the Cii data using two different model assumptions.

In the first case, we assume \( J_{\nu}^{\text{total}} \) just slightly above the background, \( J_{\nu}^{\text{total}} = 3.9 \times 10^{-20} \) erg cm−2 s−1 Hz−1 sr−1. Because this is a lower limit to the radiation field, this analysis provides an upper limit on density (i.e., for all else being constant, if we increase the radiation field, the density required to collisionally excite the Cii fine structure levels is decreased). The metallicity, dust-to-gas ratio, and log \( \xi_{\text{CII}} \) are determined by AODM over the entire profile with measured results given in Table 3. The densities and temperatures derived from the Cii fine structure data are given in Table 5.

In an attempt to refine the model, in the second case, we used the AODM over three “super-components” of the Cii*, Sii, Feii, and other low-ion and resonance line transitions. The choice of super-components was motivated by visual inspection of the spectra that reveal three large velocity components separated in velocity space (albeit with each component containing smaller substructure). We arbitrarily chose \( v = 0 \) km s−1 at \( z_{\text{abs}} = 2.054151 \), and defined the AODM super-components as follows: super-component (a) from \( v = −30 \) to \( 15 \) km s−1, super-component (b) from \( v = 15 \) to \( 70 \) km s−1, and super-component (c) from \( v = 70 \) to \( 120 \) km s−1, see Figure 20. Super-components (a), (b), and (c) coincide with Cii components (1, 2), (3, 4, 5, 6, 7), and (8, 9), respectively. We then applied the metallicity, dust-to-gas ratio, and N(Cii*) measurement derived from the AODM “super-component” to each associated Cii component. Table 9 contains a summary of this analysis. Looking at each super-component, we find the following:

**Super-component (a).** We did not perform the Cii* analysis on super-component (a) because we measure a super-solar [Fe/S] and [Ni/S]. The absence of depletion detected for Fe and Ni implies that we cannot calculate the dust-to-gas ratio. If real, this super-solar (or nearly solar) value of Feii would require a different and special star formation history. Given that we cannot calculate a dust-to-gas ratio or \( J_{\nu}^{\text{local,CII}} \), and the fact that the Cii components 1 and 2 associated with super-component (a) contain the smallest amount Cii, we did not perform further analysis.

**Super-component (b).** Super-component (b), which includes Cii components 3, 4, 5, 6, and 7, contains the bulk of the gas. The Cii* technique results in \( J_{\nu}^{\text{total,CII}} = 5.27 \times 10^{-18} \) erg cm−2 s−1 Hz−1 sr−1. The combination of the large \( J_{\nu}^{\text{total}} \) and the low \( \xi_{\text{CII}} \) is not compatible with the measurements of Cii fine structure in components 3, 4, or 5 (6 and 7 are ruled out by upper limits).

**Super-component (c).** The Cii* technique applied to super-component (c), which covers Cii components 8 and 9, results in a \( J_{\nu}^{\text{total,CII}} = 1.1 \times 10^{-19} \) erg cm−2 s−1 Hz−1 sr−1. A reasonable range of results for components 8 and 9 is summarized in Table 5.

If we relax the constraint of \( J_{\nu}^{\text{total,CII}} \) as measured by the Cii* technique, we can determine limits for each component for a range of possible radiation fields. Results are given in Table 6. In all cases, we can put a lower limit on the density of \( n > 7 \) cm−3. In all components except for component 2, the temperature can be constrained to be \( T \leq 800 \) K and the \( J_{\nu}^{\text{total,CII}} \leq 27 \times 10^{-19} \) erg cm−2 s−1 Hz−1 sr−1, is 2 orders of magnitude larger than the Haardt–Madau background and consistent with the \( J_{\nu}^{\text{total}} \) derived by the Cii* technique.

4.6.1. On the Possible Ionization of DLA 2340–00

Given the potential presence of Feiii λ1122 and the fact that the column density of DLA 2340–00, at log N(Hi) = 20.35 cm−2, is just above the DLA threshold of \( 2 \times 10^{20} \) cm−2, we considered the possibility of partial ionization of the gas. We used the AODM technique to measure Feiii/Feii in the same three “super-components” discussed above, covering Cii components 1 and 2, components 3, 4, 5, 6, and 7, and components 8 and 9, respectively, see Figure 20. Because the Feiii profile does not trace that of the low ions (see Figure 20), we cannot rule out the possibility of blending with the Lyα forest and therefore, we treat our Feiii measurements as upper limits that ultimately give no information about possible ionization.

Instead, we can rule out a high ionization factor based on the [Ar/S] measurement. Specifically, Prochaska et al. (2002) state that photoionization models in which [Ar/S] > −0.2 dex require that \( x < 0.1 \), in other words, require gas that is > 90% neutral. Using the Arii λλ 1048, 1066 transitions, excluding blending in the super-component 3 of the λ1066 transition (see Figure 20), we find [Ar/S] > −0.2 in all components (see...
Table 9)

Table 9

AODM Component Analysis of DLA 2340–00

| Super-Component | a | b | c |
|-----------------|---|---|---|
| Δν/ν _0_        |   |   |   |
| Cr Component    |   |   |   |
| (1, 2)          |   |   |   |
| (3, 4, 5, 6, 7) |   |   |   |
| (8, 9)          |   |   |   |
| N(Fe ii) (cm⁻²) | 14.55 ± 0.05 | 14.63 ± 0.04 | 14.06 ± 0.01 |
| N(S ii) (cm⁻²)  | 14.17 ± 0.01 | 14.73 ± 0.01 | 14.31 ± 0.01 |
| N(C ii) (cm⁻²)  | 12.53 ± 0.09 | 13.60 ± 0.01 | 12.99 ± 0.04 |
| N(Hi) (cm⁻²)    | 19.58 | 20.13 | 19.72 |
| [Fe]/[H]       | −0.47 ± 0.05 | −0.95 ± 0.04 | −1.10 ± 0.01 |
| [S]/[H]        | −0.56 ± 0.01 | −0.56 ± 0.01 | −0.56 ± 0.01 |
| [Fe/Met]       | 0.09 ± 0.05 | −0.39 ± 0.04 | −0.54 ± 0.01 |
| κ               | −0.06 | 0.06 | 0.09 |
| log_{10}κ      |   |   |   |
| N(C i) total    | 12.96 | 14.01 | 13.00 |
| log C i (s-1)   | 2.24 | 1.74 | 2.34 |
| η _e_           | −26.56 | −26.05 | −26.24 |
| J _ν_ local /10⁻¹₉ν | d | 52.4 | 10.8 |
| N(Fe iii) (cm⁻²) | >13.87   | <13.94   | <13.89   |
| Fe ii/Fe iii    | <0.21    | <0.21    | <0.66    |
| N(Ar i) (cm⁻²)  | 13.31    | 13.83    | 13.65    |
| [Ar]/[S]       | 0.12     | 0.08     | 0.32     |
| N(Ni ii) (cm⁻²) | 13.21 ± 0.02 | 13.50 ± 0.01 | 13.14 ± 0.02 |
| [Ni]/[H]       | −0.55 ± 0.02 | −0.82 ± 0.01 | −0.79 ± 0.02 |
| [N]/[Met]      | 0.01 ± 0.02 | −0.26 ± 0.01 | −0.23 ± 0.03 |
| κ               | −0.01    | 0.02     | 0.01     |
| logκ            |   |   |   |

Note:

a N(H i) scaled to trace N(S ii).

b Dust-to-gas ratio relative to Milky Way, defined in the text. Here, we have used S ii instead of Si ii.

c erg cm⁻² s⁻¹ Hz⁻¹ sr⁻¹.

d We did not determine J _ν_ local for this component because the super-solar Fe ii measurement.

e AODM measurements taken as upper limits because of possible blending with the forest.

f Fe ii/Fe iii ~0.3 means partially ionized, H i/H = 0.5.

If [Ar]/[S] > −0.2 then x < 0.1 but low Ar/S does not require x ≫ 0.

Table 9), indicating that x < 0.1 and that the gas is >90% neutral.

4.6.2. Molecular Hydrogen in DLA 2340–00

The total column density of molecular hydrogen, log N(H₂) = 18.20 cm⁻², where f = 0.014, is large relative to most H₂-bearing DLAs, where f is typically f ~ 10⁻⁵. We have analyzed the H₂ using VPFFIT. To allow for the best fit, we have let the H₂ component redshifts and b-values vary independently of the C i and low-ion components. We find that we require six H₂ components to achieve the best fit. In redshift space, these components lie remarkably close to the C i components 1, 2, 4, 6, 8, and 9 (Δν = ±1.4, +0.6, −2.8, +0.3, −0.4, and +0.4 km s⁻¹, respectively) and therefore we use this notation to refer to the H₂ components. Details of the H₂ measurements are given in Table 10 and example spectra in Figure 21. In Figure 22, we plot the excitation diagrams for each H₂ component and list the excitation temperature as determined by the J = 0 and J = 1 states. Additionally, we use the population of the J = 4 state to determine the radiation field as described in the Appendix. Details are given in Table 11.

While the radiation fields derived from the H₂ data are in general consistent with the C i constraints, it is interesting to note that the densities derived from the H₂ data alone, see the Appendix for details, while consistent with the C i limits, tend to be significantly higher than that required for C i. We summarize results for each component for which we could make comparisons between the different techniques:

Components 1 and 2. Excitation temperatures are in good agreement with constraints placed by the C i data, however the H₂ analysis was not completed because of the super-solar [Fe ii]/[S ii] and [Ni ii]/[S ii].

Component 4. The H₂-derived T = 276 K is consistent with the 2σ C i range of T ≈ 40–794 K. The density derived from H₂, n(H i) = 1600 cm⁻³ is not compatible with the C i limits. Finally, the H₂-derived J _ν_ local, H₂ = 2.25 × 10⁻¹⁹ erg cm⁻² s⁻¹ Hz⁻¹ sr⁻¹ is within range allowed by C i and much lower than that predicted by C ii (J _ν_ local, C ii = 52.7 × 10⁻¹⁹ erg cm⁻² s⁻¹ Hz⁻¹ sr⁻¹).

Component 6. Because we only obtained upper limits on the C i⁺ state of C i component 6 we cannot make direct comparisons in this case. We can however, compare with C i component 5. In this case, the H₂-derived T = 587 K is consistent with the 2σ C i limit T ≲ 1259 K (or T ≤ 794 depending on J _ν_). Finally, the H₂-derived J _ν_ local, H₂ = 18.8 × 10⁻¹⁹ erg cm⁻² s⁻¹ Hz⁻¹ sr⁻¹, is consistent with the limits placed by C i, however these are both much lower than the J _ν_ local, C ii predicted by the C ii technique.

Component 8. The H₂-derived T = 475 K is inconsistent with the 2σ C i limit, T ≲ 158 K. The H₂-derived density, n(H i) = 3595 cm⁻³, is also incompatible with the range allowed by C i (n(H i) = 12–209 cm⁻³). However, the H₂-derived radiation field, J _ν_ local, H₂ = 5.13 × 10⁻¹⁹ erg cm⁻² s⁻¹ Hz⁻¹ sr⁻¹ is compatible with the limits set by C i, and similar to that predicted by the C ii technique, J _ν_ local, C ii = 11 × 10⁻¹⁹ erg cm⁻² s⁻¹ Hz⁻¹ sr⁻¹.

Component 9. The H₂-derived T = 151 K is consistent with the 2σ C i limit, T ≲ 398 K. The H₂-derived density, n(H i) = 377 cm⁻³, is also nearly compatible with the range allowed by C i (n(H i) = 28–363 cm⁻³). However, the H₂-derived radiation field, J _ν_ local, H₂ = 0.43 × 10⁻¹⁹ erg cm⁻² s⁻¹ Hz⁻¹ sr⁻¹.
### Table 10

| Component | Ion | \( z_{\text{abs}} \) | \( \sigma_{z_{\text{abs}}} \) | \( b \) | \( \sigma_b \) | \( \log N \) | \( \sigma_{\log N} \) | \( T_{0, J} \) |
|-----------|-----|-----------------|-----------------|-----|-----------------|----------------|-----------------|-----------------|
| Component 1 | H2J0 | 2.054165 | 0.000001 | 2.31 | 0.07 | 15.262 | 0.040 | \ldots |
| | H2J1 | 2.054165 | \ldots | 2.31 | 0.00 | 15.94 | 0.049 | 266 \( \pm 9 \) |
| | H2J2 | 2.054165 | \ldots | 2.31 | 0.00 | 14.904 | 0.065 | 211 \( \pm 3 \) |
| | H2J3 | 2.054165 | \ldots | 2.31 | 0.00 | 14.251 | 0.049 | 191 \( \pm 1 \) |
| | H2J4 | 2.054165 | \ldots | 2.31 | 0.00 | \(<13.39\) | \ldots | 262 \( \pm 3 \) |
| | H2J5 | 2.054165 | \ldots | 2.31 | 0.00 | \(<12.90\) | \ldots | 287 \( \pm 3 \) |
| log(total N(H2)) = | 16.06 | \( f^c \) = | 1.03 \( \times 10^{-4} \) |

Component 2

| H2J0 | 2.054291 | 0.000001 | 1.25 | 0.09 | 14.657 | 0.073 | \ldots |
| H2J1 | 2.054291 | \ldots | 1.25 | 0.00 | 15.292 | 0.078 | 232 \( \pm 5 \) |
| H2J2 | 2.054291 | \ldots | 1.25 | 0.00 | 14.478 | 0.078 | 253 \( \pm 6 \) |
| H2J3 | 2.054291 | \ldots | 1.25 | 0.00 | 14.299 | 0.059 | 265 \( \pm 7 \) |
| H2J4 | 2.054291 | \ldots | 1.25 | 0.00 | \(<13.08\) | \ldots | 293 \( \pm 8 \) |
| H2J5 | 2.054291 | \ldots | 1.25 | 0.00 | \(<12.23\) | \ldots | 378 \( \pm 9 \) |
| log(total N(H2)) = | 15.47 | \( f^c \) = | 2.63 \( \times 10^{-5} \) |

Component 4

| H2J0 | 2.054573 | 0.000002 | 4.62 | 0.16 | 17.269 | 0.082 | \ldots |
| H2J1 | 2.054573 | \ldots | 4.62 | 0.00 | 17.955 | 0.054 | 276 \( \pm 2 \) |
| H2J2 | 2.054573 | \ldots | 4.62 | 0.00 | 17.045 | 0.129 | 241 \( \pm 1 \) |
| H2J3 | 2.054573 | \ldots | 4.62 | 0.00 | 15.326 | 0.028 | 136 \( \pm 1 \) |
| H2J4 | 2.054573 | \ldots | 4.62 | 0.00 | 13.812 | 0.041 | 168 \( \pm 1 \) |
| H2J5 | 2.054573 | \ldots | 4.62 | 0.00 | 13.317 | 0.139 | 203 \( \pm 2 \) |
| log(total N(H2)) = | 18.08 | \( f^c \) = | 1.06 \( \times 10^{-2} \) |

Component 6

| H2J0 | 2.054714 | 0.000001 | 5.06 | 0.11 | 15.997 | 0.047 | \ldots |
| H2J1 | 2.054714 | \ldots | 5.06 | 0.00 | 16.825 | 0.065 | 587 \( \pm 9 \) |
| H2J2 | 2.054714 | \ldots | 5.06 | 0.00 | 16.059 | 0.039 | 349 \( \pm 8 \) |
| H2J3 | 2.054714 | \ldots | 5.06 | 0.00 | 15.836 | 0.019 | 300 \( \pm 6 \) |
| H2J4 | 2.054714 | \ldots | 5.06 | 0.00 | 14.355 | 0.015 | 286 \( \pm 4 \) |
| H2J5 | 2.054714 | \ldots | 5.06 | 0.00 | 13.932 | 0.040 | 310 \( \pm 3 \) |
| log(total N(H2)) = | 16.98 | \( f^c \) = | 8.51 \( \times 10^{-4} \) |

Component 8

| H2J0 | 2.054986 | 0.000001 | 3.64 | 0.10 | 15.76 | 0.042 | \ldots |
| H2J1 | 2.054986 | \ldots | 3.64 | 0.00 | 16.55 | 0.067 | 475 \( \pm 6 \) |
| H2J2 | 2.054986 | \ldots | 3.64 | 0.00 | 15.63 | 0.047 | 271 \( \pm 1 \) |
| H2J3 | 2.054986 | \ldots | 3.64 | 0.00 | 15.13 | 0.027 | 220 \( \pm 1 \) |
| H2J4 | 2.054986 | \ldots | 3.64 | 0.00 | 13.75 | 0.046 | 251 \( \pm 1 \) |
| H2J5 | 2.054986 | \ldots | 3.64 | 0.00 | 11.90 | 3.520 | 207 \( \pm 8 \) |
| log(total N(H2)) = | 16.67 | \( f^c \) = | 4.21 \( \times 10^{-4} \) |

Component 9

| H2J0 | 2.055135 | 0.000001 | 1.80 | 0.07 | 16.735 | 0.074 | \ldots |
| H2J1 | 2.055135 | \ldots | 1.80 | 0.00 | 17.200 | 0.057 | 151 \( \pm 5 \) |
| H2J2 | 2.055135 | \ldots | 1.80 | 0.00 | 16.035 | 0.088 | 159 \( \pm 2 \) |
| H2J3 | 2.055135 | \ldots | 1.80 | 0.00 | 14.753 | 0.049 | 135 \( \pm 3 \) |
| H2J4 | 2.055135 | \ldots | 1.80 | 0.00 | \(<13.10\) | \ldots | 162 \( \pm 3 \) |
| H2J5 | 2.055135 | \ldots | 1.80 | 0.00 | \(<13.02\) | \ldots | 212 \( \pm 3 \) |
| log(total N(H2)) = | 17.35 | \( f^c \) = | 2.00 \( \times 10^{-3} \) |

**Notes.**

\( a \) Excitation temperature between rotational level \( J \) and \( J = 0 \).

\( b \) Components are numbered by the closest \( z \) \( C_1 \) component.

\( c \) \( f \) calculated assuming \( \log N(H_1) = 20.35 \).
while compatible with the limits set by C\textsc{i}, is not compatible with that predicted by the C\textsc{ii} technique, $J_v^{\text{total,C\textsc{ii}}} = 11 \times 10^{-19}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$.

A striking difference is seen in the densities derived from the C\textsc{i} and H\textsc{2} data. A similar difference has been reported in sight lines toward Q0013$-$004 and Q1232+082 (Hirashita & Ferrara 2005) and HE0515$-$00 (Reimers et al. 2003; Quast et al. 2002). They argue that if the density is this high, i.e., equal to the critical density, then the states should be thermalized and there would be no difference in the excitation temperature as determined by the $J=1$ and $J=2$ states. Given that the observed $T_{02}$ is always much greater than $T_{01}$, Hirashita & Ferrara (2005) propose, following the suggestion of Reimers et al. (2003), that a potential explanation may be that the H\textsc{2} formation rate ($R_{\text{dust}}$) may be larger than estimated, which would result from, for example, a smaller than estimated grain size. Therefore, if the formation
rate is higher, you require a smaller density than that derived. On the other hand, for each component of DLA 2340−00 studied here, the $T_0$ is either less than or approximately the same as $T_01$, implying that the critical density cannot be ruled out.

5. DISCUSSION

We have used C$\text{I}$ fine structure absorption in high-resolution, high signal-to-noise data to study the physical conditions in DLAs at high redshift. Our work differs from previous studies of C$\text{I}$ fine structure absorption because we did not assume a gas temperature in order to derive the density. Rather, we assume ionization equilibrium, which in conjunction with the C$\text{I}$ fine structure data, allows us to constrain both the temperature and the density of the cloud. In addition, we use the C$\text{II}$ technique to infer the local radiation field due to stars and include its contribution to the C$\text{I}$ fine structure excitation, thus providing a complete and fully self-consistent model of the gas. In most cases, the C$\text{I}$ fine structure excitation is consistent with the $f_{\text{local}}$ C$\text{II}$, derived independently by the C$\text{II}$ technique.

5.1. Assessment of Systematic Errors

To draw meaningful comparisons between the C$\text{I}$ results and those of the C$\text{II}$ technique, we must first analyze our possible systematic errors. The primary source of error in the C$\text{I}$ analysis stems from two sources—(1) measurement error of the fine structure column densities, including possible errors in the oscillator strengths (we report results for 2σ errors, which should encompass these errors), and (2) the assumption that in solar units the carbon abundance is equal to that of Si$\text{II}$ (or Si $\text{II}$) −0.2 dex in case of minimal depletion. The source of systematic errors in the C$\text{II}$ technique is more difficult to assess (see WGP03 for a complete discussion). We explore the possible effects of these errors in the following section and demonstrate that, even considering these errors, the C$\text{I}$ data appear to be probing gas of higher densities and pressures—likely small knots of gas within the larger DLA galaxies—than that probed by the “global” C$\text{II}$ technique.

5.1.1. Comparison with C$\text{II}$ Technique Model

While it is difficult to assess the systematic errors involved in the C$\text{II}$ technique, some of the potential uncertainties have been removed since the work of WGP03. For example, the Small Magellanic Cloud (SMC) dust model is now assumed to be correct because of the non-detection of the 2175 Å dust feature that would have indicated Galactic dust, while the reddening curve resembles SMC rather than Galactic or Large Magellanic Cloud (LMC; Vladilo et al. 2008). Therefore, we focus on the two largest potential uncertainties: (1) the assumption of the equilibrium pressure, $P_{\text{eq}}$, and (2) the minimal versus maximal, depletion model (see discussion in Section 2.3 of WGP03). The standard C$\text{II}$ technique involves solving the equations of thermal and ionization equilibrium as described in WPG03 and Wolfire et al. (1995). A unique solution is determined by assuming that the equilibrium pressure is equal to the geometric mean between $P_{\text{max}}$ and $P_{\text{min}}$, $P_{\text{eq}} = P_{\text{geo}} = (P_{\text{min}} P_{\text{max}})^{1/2}$, where $P_{\text{min}}$ and $P_{\text{max}}$ are the minimum and maximum pressures of the function $P(n)$ where $n$ is gas density. This results in two stable solutions for a given star formation rate, one WNM and one CNM, and is the basis of the two-phase model. However, a two-phase medium can achieve equilibrium with a pressure ranging from $P_{\text{min}}$ to $P_{\text{max}}$, and therefore, the assumption of $P_{\text{eq}}$ equal to the geometric mean, while reasonable (see Wolfire et al. 2003; WPG03 discussion), is still an unproven assumption. Following WGP03, we attempt to gain a sense of the possible systematic errors by allowing $P_{\text{eq}}$ to vary between $P_{\text{min}}$ and $P_{\text{max}}$. In Figure 23, we show the standard two-phase diagram, plotting in (a), log($P/k$) versus density for various star formation rates per unit area (which is proportional to $J_\nu$) which are constant along each $P(n)$ curve, and which increase from bottom to top, and in (b) log($\ell_c$) versus density for $\ell_c$, equilibrium solutions for those same star formation rates. The green dashed line in each plot indicates the $P(n)$ solution for heating by background radiation alone (i.e., log $\Sigma_{\text{SFR}} = -\infty$). The black horizontal line in (b) denotes the observed cooling rate of DLA 1331+17, log($\ell_c$) $\leq -27.14$ erg s$^{-1}$ H$^{-1}$. Three vertical, black, dotted lines illustrate the location of the CNM, CNM stable points associated with, from left to right, $P_{\text{min}}$, $P_{\text{geo}} = (P_{\text{min}} P_{\text{max}})^{1/2}$, and $P_{\text{max}}$ for the case of background radiation alone. The stable ($\ell_c, n$) pairs for the grid of star formation rates are denoted by the three red lines in (b), where the three different pressure assumptions have been made—from left to right they are dashed: $P_{\text{min}}$, dot-dashed: $P_{\text{geo}}$, and dotted: $P_{\text{max}}$. Although not relevant for our current discussion, it is seen that $P_{\text{min}}$ requires a higher star formation rate and lower density to achieve an equilibrium solution with a cooling rate equal to that observed. On the opposite extreme, $P_{\text{max}}$ requires a higher density and lower star formation rate.

For the purposes of this paper, we are interested in the range of densities and temperatures that result from these different model assumption inputs to the C$\text{II}$ technique. In Figure 24, we plot the resultant log($P/k$) versus density for our example case of DLA 1331+17. For the minimal depletion model, the case of $P_{\text{eq}} = P_{\text{geo}} = (P_{\text{min}} P_{\text{max}})^{1/2}$ is denoted by the asterisk. Lines connect to the $P_{\text{min}}$ and $P_{\text{max}}$ solutions, providing a sense for the potential systematic “error” involved in the assumption of where the equilibrium pressure resides. We have also plotted the results of the maximal depletion model, denoted by the diamond, with dashed lines connecting to the associated $P_{\text{min}}$ and $P_{\text{max}}$ solutions. To correctly compare this range of solutions to that of the C$\text{I}$ data, we must re-model the C$\text{I}$ theoretical curves in each case because the change in the assumed $P_{\text{eq}}$ results in a change of star formation rate, or $J_\nu$ local, which is an input for the C$\text{I}$ theoretical curves. We plot the 2σ results of the C$\text{I}$ analysis for $J_\nu$ local spanning that determined by $P_{\text{min}}$ and $P_{\text{max}}$. We summarize the results of these two techniques for DLA 1331+17 in Table 12.

In Figure 25, we summarize the results of our C$\text{I}$ sample and compare them to the C$\text{II}$-derived and H$_2$-derived models of the same systems. We plot the best-fit C$\text{I}$ solutions, as determined by $\chi^2$ minimization, as circles, while the shaded regions denote the 2σ C$\text{I}$ solutions. The C$\text{II}$ solutions are represented as diamonds. It is seen that the densities determined by the C$\text{II}$ technique are systematically lower than those determined by the C$\text{I}$ data. As a result, the overall pressures are lower. The temperatures vary depending on model assumptions, but are in general agreement or higher than the C$\text{I}$ results (see Table 12). We conclude that the C$\text{I}$ gas is tracing a denser region of the DLA than that traced by the global C$\text{II}$ technique: essentially, the C$\text{I}$ resides primarily in small, overdense knots. However, one problem with this picture is understanding how these two phases, the low-pressure ambient medium and the
higher-pressure smaller “clumps” of C i-bearing gas, remain in pressure equilibrium. We return to this issue in a following paper.

These comparisons also reveal a discrepancy between the C ii derived by the C ii* technique analysis and the observed C ii. In general, the observed C ii//C i ratio is approximately an order of magnitude smaller than that predicted by the C ii* technique model (see Table 12). We avoid a detailed discussion here and refer the interested reader to WGP03, Section 5.1, for a detailed discussion of the model inputs that affect C ii//C i. We only briefly mention that we have tested the results with cosmic rays turned on and off, and there is not a large effect on the results for the star formation rates we are considering. However, this is not the case for large star formation rates, J total ν ∼ 10^{-18} erg cm^{-2} s^{-1} Hz^{-1} sr^{-1}, for which the effect of cosmic rays becomes more important. Assuming that the C ii* technique model is correct, we can understand this difference in terms of the new model in which the bulk of the measured C i is localized in small, dense clumps, ≈ 1–10 pc, relative to the larger DLA (for estimates of the cloud size, see last column in Table 5). In this case, while the cloud is still optically thin and feels the same radiation field
J agree to within increased electron density, as the surrounding medium, the increased density, and hence, the technique median values for the same DLAs: $\chi_\text{fit}$ (minimized technique (diamonds). The 2

![Figure 25](image)

Figure 25. Summary of all DLAs, compared with the results of the C n $\text{technique (diamonds).}$ The 2 $\nu$ C1 results are the shaded regions, and the best fit (minimized $\chi^2$) for each is marked by a filled circle. It is clear that the C1 results are consistently higher in density and therefore pressure. Note, some regions/solutions are overlapping. The H$_2$-derived pressures are denoted by light grey crosses and asterisks for components in DLA 0812+32 and DLA 2340$-$00, respectively. The solid black line denotes $T = 10\ K.$ The resulting median values for the C1 sample are $\langle n(\text{H}1) \rangle = 69\ cm^{-3}, \langle T \rangle = 50\ K,$ and $(\log(P/k)) = 3.86\ cm^{-3}\ K,$ with standard deviations, $\sigma_{\text{fit}} (\text{H}1) = 134\ cm^{-3}, \sigma_T = 52\ K,$ and $\sigma_{\log P/k} = 3.68\ cm^{-3}\ K.$ This can be compared with the global C n $\text{technique median values for the same DLAs:}$ $\langle n(\text{H}1) \rangle = 2.8\ cm^{-3}, \langle T \rangle = 139\ K,$ and $(\log(P/k)) = 2.57\ cm^{-3}\ K,$ with standard deviations $\sigma_{\text{fit}} (\text{H}1) = 3.0\ cm^{-3}, \sigma_T = 43\ K,$ and $\sigma_{\log P/k} = 0.22\ cm^{-3}\ K.$ (A color version of this figure is available in the online journal.)

as the surrounding medium, the increased density, and hence, increased electron density, $n_e,$ of the C1 cloud work to lower C1 because $\alpha_{\text{fit}}$ is inversely proportional to density for a fixed radiation field. In a sense, this conflict with the predictions of the “global” C n $\text{technique model, is an expected result of the overdense-C1-region model.}$

5.1.2. Direct Estimate of Error on $J_{\nu}^\text{local}$

While there are many assumptions and uncertainties in the C n $\text{technique, we can make a direct estimate of the possible error on } J_{\nu}^\text{local} \text{ derived from the C n $\text{technique by using the } z_{\text{abs}} = 1.9 \text{ DLA 2206$-$19}.}$ In Wolfe et al. (2004), the FUV radiation field inferred from an image of a galaxy associated with this DLA (Warren et al. 2001) is compared with the radiation field inferred from the C n $\text{technique and they are found to agree to within } \sim 50\%.$ Therefore, we will assume that the error on $J_{\nu}^\text{local}$ is $\sim 50\%.$

5.1.3. Distribution of C II

Throughout this work, we assume that the measured N(C II) can be directly applied to each C1 cloud. However, assuming that there is no hidden saturation—which would actually increase the N(C II)—this is actually an upper limit to the amount of N(C II) associated with each C1 cloud. The distribution of C1 along the line of sight could be clumpy such that only a fraction of the measured N(C II) is associated with a given C1 cloud. With respect to the analysis done in this paper, the effect of decreasing the amount of C II associated with the C1 cloud causes an increase in the resultant volume density and a decrease in the temperature such that the pressure remains approximately constant. The increase in volume density with decreasing fraction of C II results in a decrease of the derived cloud size as shown in Figure 26.

![Figure 26](image)

Figure 26. Resultant cloud size in pc (top axis) as a function of the fraction of C n, $f(\text{C n, associated with the C1 cloud.}$ Here, $f(\text{C n}) = 1 \text{ means that } 100\% \text{ of the measured N(C n) is associated with the C1 cloud.}$ In this case, for DLA 0812+32, component 3, log($F(\text{C n})$) $= 3.1 \pm 0.2.$ As the fraction of associated C n decreases, the $n(\text{H}1)$ increases and hence, the resultant cloud size decreases.

5.2. Relation to “High-cool” DLA Population

With the exception of DLA 1331$+$17, all of the C1-bearing objects not only contain C n (as compared with $\sim 50\%$ of the general DLA population) but also have cooling rates, $\ell_c,$ that place them firmly in the “high-cool” range defined by Wolfe et al. (2008) (median “high-cool” $\log \ell_c = -26.6\ erg\ s^{-1}\ H^{-1}.$) A literature search reveals that all previously published DLAs with positive detections of C1 fall into the “high-cool” population as well. While it is not clear how the bimodality discovered by Wolfe et al. (2008) is related to C1, this correlation—that almost all C1-bearing DLAs are also high-cool DLAs—could simply be a result of the higher metallicities and dust-to-gas ratios that are required to form and sustain, through dust shielding of UV radiation, measurable amounts of H$_2$ and C1. This trend, of higher metallicity DLAs being more likely to contain measurable H$_2,$ has been observed previously by Petitjean et al. (2006). Additionally, the “high-cool” DLAs, shown by Wolfe et al. (2008) to consist of primarily CNM, simply might be an environment more conducive to the presence of H$_2$ and C1.

5.3. Comparison with the Local ISM

In this section, we compare our C1-bearing clouds to the ISM of the local universe, namely, the Milky Way and the SMC and LMC, respectively. To draw these comparisons, we first determine the median $n(\text{H}1), T,$ and $P$ of our C1 sample. Of course, this median is dependent upon which models we choose to include. Here, we include the models for each DLA that are likely to be the most physically realistic, i.e., case (a), the low-$\ell_c,$ minimal depletion model for DLA 0812+32, $z_{\text{abs}} = 2.06,$ and the “global” models for both DLA 0812+32, $z_{\text{abs}} = 2.62$ and DLA 2340$-$00. We chose the “global” models as the most likely to be correct because of the inherent uncertainty in determining the distribution of both the $N(\text{H}1)$ and the metals amongst the velocity components necessary for the component by component analysis. A summary of these models is shown in Figure 25. The resulting median values for this sample are $\langle n(\text{H}1) \rangle = 69\ cm^{-3}, \langle T \rangle = 50\ K,$ and $(\log(P/k)) = 3.86\ cm^{-3}\ K.$
with standard deviations, \( \sigma_{n(H)} = 134 \text{ cm}^{-3} \), \( \sigma_T = 52 \text{ K} \), and \( \sigma_{\log P/k} = 3.68 \text{ cm}^{-3} \text{ K} \).

In the Milky Way, Jenkins & Tripp (2001) used very high resolution (\( R = 200,000 \)) STIS data to analyze C1 fine structure populations and find a median \( \log(P/k) = 3.35 \text{ cm}^{-3} \text{ K} \). This median pressure is similar to the pressures we derive in high-redshift C1-bearing DLAs, where the median pressures derived are typically \( \log(P/k) = 3–4 \text{ cm}^{-3} \text{ K} \). While this would seem to indicate that physical conditions similar to the Milky Way exist in high-z DLAs, we point out that in the case of the Milky Way, the high pressure is driven by the much higher heating rate (\( \log \epsilon_\nu \sim -25 \text{ erg s}^{-1} \text{ H}^{-1} \)), a result of the higher dust-to-gas ratio (typically 30 times that of DLAs). In contrast, the heating rates in high-redshift DLAs are generally 1–2 orders of magnitude smaller. Hence, the pressures derived in the C1-bearing clouds, while similar to those observed in the Milky Way, are not the result of the same physical conditions as those observed in the Milky Way. Jenkins & Tripp (2001) also observe a small proportion of the gas in many sight lines to be at very high pressures, \( P/k > 10^5 \text{ cm}^{-3} \text{ K} \), which they speculate are caused by converging flows in a turbulent medium or in turbulent boundary layers: such pressures have not been detected in DLAs.

It is perhaps more meaningful to compare DLAs with the LMC and SMC that, like DLAs, are known to have sub-Milky Way dust-to-gas ratios and metallicities. Tumlinson et al. (2002) performed a FUSE survey of H2 along 70 sight lines to the SMC and LMC and in better agreement with the mean kinetic temperature \( T = 77 \pm 17 \text{ K} \) (Savage et al. 1977). The temperatures found by the C1 and H2 data presented here are in broad agreement with these values. A noticeable exception to this agreement are the temperatures derived from the H2 rotational states in DLA 2340–00. They are generally higher (\( T_{\text{ex}} \approx 150–600 \text{ K} \)) than those found in the SMC/LMC and in better agreement with the mean kinetic temperature of the gas, \( T = 153 \pm 78 \text{ K} \), found by Srianand et al. (2005) in a sample of H2-bearing DLAs at high-z.

## 6. CONCLUSIONS

The goal of this paper is to present new detections of neutral carbon in high-redshift DLAs and to present a new method for analyzing the C1 fine structure lines. As done by several other authors, we utilize C1 fine structure lines to determine densities, however, instead of assuming a temperature, our work constrained the allowed density and temperature combinations using only the column density of C1 in the fine structure states and the assumption of ionization equilibrium. In a second paper, we will incorporate these physical conditions into a general model for C1-bearing DLAs. Our major conclusions are as follows:

1. The steady state analysis of C1 fine structure populations along with the assumption of ionization equilibrium provides realistic constraints on both the volume density \( n(H) \) and temperature of high-redshift DLAs. The C1 data are in general consistent with the radiation fields, \( J_\nu^{\text{local,C1}} \), derived from the C1 technique and provide further evidence of the presence of CNM in high-redshift DLAs.

2. The densities and pressures of the C1-bearing gas are systematically higher than those of the “global” DLA predicted by the C1 technique. We propose two physical scenarios that could be consistent with the data presented here. First, the C1 could be tracing overdensities that are created by shocks, hence the C1 exists in the post-shock cool gas. However, it seems likely that the post-shock gas would have a systemic velocity offset from the pre-shock gas. This is not observed. In fact, the general good agreement between the velocity centroids of the C1 and other resonance lines argues against the shock idea. A second scenario is that the C1 exists in higher-density, higher-pressure edge of a photodissociation region, i.e., the edge of a molecular cloud. While the high optical depth through a classical molecular cloud would obscure a background quasar, the photodissociation region, or edge of the molecular cloud could be optically thin enough to allow transmission of the background quasar light and would be consistent with the gas physics determined by the C1 fine structure lines.

3. As noted by Srianand et al. (2005), all C1-bearing DLAs also contain C1 near infrared and far infrared absorption lines. We find that, with only one exception, all C1 objects for which C1 near infrared absorption is available (five presented in this paper, one yet to be published, and seven from the literature) contain strong C1 absorption, placing them in the category of “high-cool” DLAs. This could be simply a consequence of the fact that C1-bearing DLAs generally host larger fractions of H2 whose formation is encouraged by the higher than average metallicities and dust-to-gas ratios, consistent with the “high-cool” population of DLAs.

4. High-resolution studies of neutral carbon lines reveal narrow, sub-1 km s\(^{-1}\), cold and unresolved components. These components likely contain relatively large amounts of gas and are most likely cold, dense knots, perhaps photodissociation regions on the edges of star-forming regions. This would explain the presence of C1, H2, and larger than average dust-to-gas ratios. To date, two such components have been published; in DLA 0812+32 with a temperature of \( T < 78 \text{ K} \) (Jorgenson et al. 2009) and in DLA 1331+17 with \( T < 218 \text{ K} \) (Carswell et al. 2010) and we presented an additional candidate in this paper. Such clouds may exist in all C1 systems. Their non-detection in other C1 systems does not rule out their existence due to the difficulty in detecting such small equivalent widths that are likely blended with other velocity components. It is possible that these narrow components are ubiquitous and contain significant amounts of gas that has been previously missed in lower resolution studies.

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## APPENDIX

**MOLECULAR HYDROGEN**

The purpose of this appendix is to present an outline of the molecular hydrogen analysis performed in this work. While the focus of this work was the analysis of neutral carbon, DLAs that contain neutral carbon are likely to also contain detectable...
H2. This is because neutral carbon and molecular hydrogen are photoionized and photodissociated respectively, by photons of the same energies and therefore, they are usually found together. This is the case in several of the DLAs presented in this work, i.e., DLA 1331+17, DLA 0812+32, and DLA 2340−00. For DLA 2231−00 and the low-ζ DLA 0812+32, we did not have coverage of the H2 region and therefore cannot determine anything about the presence of H2. Here, we present an outline of the DLA H2 analysis frequently performed in the literature, most recently by works such as Levshakov et al. (2002), Hirashita & Ferrara (2005), Cui et al. (2005), Noterdaeme et al. (2007b), and Noterdaeme et al. (2007a) and based upon work by Spitzer & Zweibel (1974), Jura (1975a), and Jura (1975b). Essentially, the measurement of H2 in the different rotational J states allows for an independent estimation of the physical properties of the cloud such as density, temperature, and the incident radiation field. While the H2 analysis arguably contains several uncertainties and assumptions, it is nonetheless interesting to compare the results from these two independent methods, the H2 analysis we present below and the C I fine structure analysis presented in this work.

First, we can estimate the kinetic temperature of the cloud using the column densities of H2 in the J = 0 and higher J rotational states. According to the Boltzmann distribution (see Equation (8) in Levshakov et al. 2002),

$$\frac{N(J)}{N(0)} = \frac{g(J)}{g(0)} e^{-\frac{B_J(J+1)}{T_{ex}}}.$$  \hspace{1cm} (A1)

where $B_J = 85.36$ K for the vibrational ground state and $g(J)$ is the degeneracy of level J, given by, for level $J = x$, $g_J = (2J + 1)(2I + 1)$ where $J = 0$ for even $x$ and $J = 1$ for odd $x$ (For states $J = 0$–5, $g = [1, 9, 5, 21, 9, 33]$). The excitation diagram is typically plotted as $\log(N_J/g_J)$ versus the relative energy between the level $J$ and $J = 0$. The excitation temperature, defined in Equation (A1), is inversely proportional to the negative slope of the line connecting the excitation diagram points, i.e.,

$$T_{ex}^{0J} = -\frac{1}{B_J(J+1)} \frac{1}{\ln \frac{g_J}{g_0}}.$$  \hspace{1cm} (A2)

The typical assumption is that the kinetic temperature of the cloud can be estimated by the excitation temperature derived from the population of H2 in the states $J = 0$ and $J = 1$, assuming that the $J = 1$ level is thermalized. Because the critical density of the low J states is relatively small, the population of the low J levels is generally dominated by collisional excitation and therefore it reflects the kinetic temperature of the gas when in local thermodynamical equilibrium. The higher J states ($J \geq 2$) are typically characterized by a higher $T_{ex}$, or flatter slope, which is explained by population mechanisms other than collisions.

The higher $T_{ex}$ derived from the population of H2 in the higher rotational J states was originally unexpected (Spitzer & Zweibel 1974). After observations by Spitzer and Chochran in the 1970s in which they observed the high excitation temperatures derived from the high J states, Spitzer & Zweibel (1974) proposed methods other than collisions that could populate the higher J states. They proposed two methods other than collisions: (1) the cascade down from upper vibrational levels following the absorption and reemission of Lyman and Werner band photons—i.e., the $J = 0$ molecule is excited to a higher vibrational state and then de-excites to a higher J state in the ground vibrational state (rather than staying in the original $J = 0$ or $J = 1$ state), or (2) the direct formation of H2 in a higher state (i.e., the H2 pops off the dust particle in an excited state and cascades to say $J = 4$). Since these processes are believed to dominate collisions, the typical practice is to neglect collisions and to consider only these two processes, as we show in the following analysis.

Assuming steady state and neglecting collisions, we use the two afore mentioned populating mechanisms and assume depopulation by spontaneous emission (true until the density is above $10^4$), to write the following steady state equations for state $J = 4$ and $J = 5$, respectively (these are Equations (2a) and (2b) from Jura 1975b),

$$p_{4,0} \beta_0 n(H_2, J = 0) + 0.19 Rn(H_1)n(H) = A_{4,2} n(H_2, J = 4)$$ \hspace{1cm} (A3)

and

$$p_{5,0} \beta_0 n(H_2, J = 1) + 0.44 Rn(H_1)n(H) = A_{5,3} n(H_2, J = 5),$$ \hspace{1cm} (A4)

where $p$ is the pumping coefficient or pumping efficiency (or by Jura, the redistribution probability) into the $J = 4$ and $J = 5$ levels from the $J = 0$ and $J = 1$ levels, respectively, $\beta$ is the photoabsorption rate, $R$ is the H2 molecule formation rate (on dust grains, also known as $R_{dust}$), $n(H)$ is the neutral hydrogen number density, $n(H) \approx n(H_1) + 2n(H_2)$, and $A$ is the spontaneous transition probabilities. In other words, the first term is the UV excitation and decay to higher J state, while term 2 represents the direct formation in the higher J state. The values of the constants are as follows: $A_{4,2} = 2.75 \times 10^{-9}$ s$^{-1}$, $A_{5,3} = 9.9 \times 10^{-9}$ s$^{-1}$ (Spitzer 1978), $p_{4,0} = 0.26$, $p_{5,1} = 0.12$ (Jura 1975b). Solving for $\beta$ will allow us to estimate the UV field incident on the cloud, while $\beta$ together with $R$ will allow us to estimate the neutral hydrogen density.

In order to solve for $\beta$ and to get rid of the $N(H_1)$ dependence in Equation (A3), we take advantage of the assumption of equilibrium between the formation and the destruction of H2 (which is reasonable because the timescales of H2 formation and destruction are well below a dynamical time), as follows:

$$Rn(H_1)n(H) = R_{diss} n(H_2).$$ \hspace{1cm} (A5)

If we substitute Equation (A5) into Equation (A3), and make the common assumption that 11% of photoabsorption leads to photodissociation (Jura 1974b),

$$R_{diss} = 0.11 \beta$$ \hspace{1cm} (A6)

we obtain equilibrium equations that are independent of the neutral hydrogen column density $N_{H_1}$.

$$p_{4,0} \beta_0 \frac{N(H_2, J = 0)}{N(H_2)} + 0.021 \beta_0 = A_{42} \frac{N(H_2, J = 4)}{N(H_2)}$$ \hspace{1cm} (A7)

and

$$p_{5,0} \beta_1 \frac{N(H_2, J = 1)}{N(H_2)} + 0.049 \beta_1 = A_{53} \frac{N(H_2, J = 5)}{N(H_2)}.$$

Using the measured H2 column densities we can then solve for $\beta$, the photoabsorption rate of H2 in each component. Note, that $\beta_0$ should equal $\beta_1$.

Once we have solved for $\beta$ we can determine the incident radiation field by using the relation between the radiation field and the photodissociation rate that it induces on the molecular...
hydrogen. Following Abel et al. (2004) and Hirashita & Ferrara (2005),
\[
R_{\text{diss}} = (4\pi)1.1 \times 10^5 J_{\nu}^{\text{LW}} S_{\text{shield}} \text{s}^{-1},
\]
where \(R_{\text{diss}}\) is the photodissociation rate (= 0.11 \(J\) as above), \(J_{\nu}^{\text{LW}}\) (LW stands for Lyman–Werner) is the UV intensity at \(\nu\) = 12.87 eV averaged over the solid angle (12.87 eV is the dominant energy at which the photodissociation happens). This can be compared with the \(J_\odot\) that is typically calculated in the C1+ technique at \(\lambda = 1500 \, \text{Å}, or 8.27 \, \text{eV}\). \(S_{\text{shield}}\) accounts for shielding due to two effects: (1) dust shielding and (2) self-shielding. In order to solve for \(J_{\nu}^{\text{LW}}\) we must determine the effects of shielding in Equation (A9). We estimate the shielding, following Hirashita & Ferrara (2005), as
\[
S_{\text{shield}} = \left( \frac{N(H_2)}{10^{14} \, \text{cm}^{-2}} \right)^{-0.75} e^{-\sigma_d N_d},\]
where the first term expresses the self-shielding and the exponential term is the shielding due to dust. \(N_d\), the column density of dust, is related to the \(\text{H}^+\) column density by \((4/3)\pi \delta N_d = 1.4 m_H N_H D\), where 1.4 is the correction for the helium content, and \(\sigma_d\) is the cross-section of a grain, \(\sigma_d = \pi a^2\). \(\sigma_d N_d = \tau_{\text{UV}}\) is the optical depth in dust and is expressed by Hirashita & Ferrara (2005) as
\[
\tau_{\text{UV}} = \frac{4.2 N_H m_H D}{4a\delta}
= 0.879 \left( \frac{a}{0.1 \, \mu m} \right)^{-1} \left( \frac{\delta}{2g \, \text{cm}^{-3}} \right)^{-1} \left( \frac{D}{1021 \, \text{cm}^{-2}} \right)^{-1} \left( \frac{N_H}{10^{21} \, \text{cm}^{-2}} \right)^{-1},\]
where \(a\) is the radius of a grain, \(\delta\) is the grain material density, and \(D\) is the dust-to-gas mass ratio. Hirashita & Ferrara (2005) assume the Galactic (Milky Way) dust-to-gas mass ratio to be \(D_\odot = 0.01\). They define the normalized dust-to-gas ratio \(\kappa = D/D_\odot\). Assuming \(a = 0.1\) and \(\delta = 2\), Equation (A11) can be written
\[
\tau_{\text{UV}} = 0.879\kappa \left( \frac{N_H}{10^{21} \, \text{cm}^{-2}} \right)^{-1},\]
see Cui et al. (2005) Equation (7).

The first part of Equation (A10), the self-shielding of \(H_2\), is taken from an analytic approximation from Draine & Bertoldi (1996) and is valid for \(N(H_2) > 10^{14} \, \text{cm}^{-2}\). We can therefore rewrite Equation (A10) as
\[
S_{\text{shield}} = \left( \frac{N(H_2)}{10^{14} \, \text{cm}^{-2}} \right)^{-0.75} \exp \left[ -0.879\kappa \left( \frac{N_H}{10^{21} \, \text{cm}^{-2}} \right) \right].\]

Therefore, given \(\beta\) and \(S_{\text{shield}}\) we can use Equation (A9) to solve for the ambient radiation field, \(J_{\nu}^{\text{LW}}\). Note that this is the total radiation field, or \(J_{\nu}^{\text{LW}} = J_{\nu}^{\text{total}}\).

We can also use the measurements of \(N(H_2)\) to estimate the volume density of \(\text{H}^+\). We define the molecular fraction, \(f_{H_2}\) as follows:
\[
f_{H_2} = \frac{2n(H_2)}{n(H^+) + 2n(H_2)} = \frac{2N(H_2)}{N(H^+) + 2N(H_2)},\]
where we measure the \(N(H^+)\) and the \(N(H_2)\) directly. If we substitute Equation (A14) into (A5) and remember that \(n(H) \approx n(H^+) + 2n(H_2)\), we can solve for the number density of hydrogen,
\[
R n(H) = R_{\text{diss}} \frac{n(H_2)}{n(H^+) + 2n(H_2)} = \frac{R_{\text{diss}} f_{H_2}}{2},\]
or
\[
n(H_2) = \frac{R_{\text{diss}} f_{H_2}}{R} \frac{2}{2},\]
This is temperature dependent however, and we will use the detailed expression for \(R\) given by Hirashita & Ferrara (2005) (note, they call it \(R_{\text{dust}}\)).
\[
R = 4.1 \times 10^{-17} S_d(T) \left( \frac{a}{0.1 \, \mu m} \right)^{-1} \left( \frac{D}{10^{-2}} \right) \left( \frac{T}{100 \, \text{K}} \right)^{1/2} \times \left( \frac{\delta}{2g \, \text{cm}^{-3}} \right)^{-1},\]
where \(S_d(T)\) is the sticking coefficient of hydrogen atoms onto dust and everything else was defined previously. The sticking coefficient is given by (Hollenbach & McKee 1979; Omukai 2000)
\[
S_d(T) = [1 + 0.04(T + T_d)^{0.5} + 2 \times 10^{-3} T + 8 \times 10^{-6} T^2]^{-1} \times (1 + \exp[7.5 \times 10^2(1/75 - 1/T_d)])^{-1},\]
where \(T_d\) is the dust temperature and is given by
\[
T_d = 12(\chi Q_{\text{UV}})^{1/6} \left( \frac{A}{3.2 \times 10^{-13} \, \text{cm}} \right)^{-1/6} \left( \frac{a}{0.1 \, \mu m} \right)^{-1/6} \text{K},\]
where \(A\) is a constant that depends on the optical properties of the dust grains. For silicate grains, \(A = 1.34 \times 10^{-3}\) cm and for carbonaceous grains, \(A = 3.2 \times 10^{-3}\) cm. Following Hirashita & Ferrara (2005), we assume \(Q_{\text{UV}} = 1\). (\(Q_{\text{UV}}\) is the dimensionless absorption cross-section normalized by the geometrical cross-section), \(A = 3.2 \times 10^{-3}\) cm and \(a = 0.1 \, \mu m\), while \(\chi\), the normalized radiation field, was calculated previously from the \(H_2\) levels (\(\chi = J_{\nu}^{\text{LW}} / J_{\nu}^{\text{LW}}\) where \(J_{\nu}^{\text{LW}} = 3.2 \times 10^{-20} \, \text{erg} \, \text{cm}^{-2} \, \text{s}^{-1} \, \text{Hz}^{-1} \, \text{sr}^{-1}\)). Therefore, we can determine \(R\) as a function of \(T\). In the present work, we assume that \(T\) is equal to the excitation temperature as derived from the \(J = 0\) and \(J = 1\) states. Finally, we use Equation (A16) to estimate the neutral hydrogen density. Note, this method of determining temperature, density and radiation field, is independent of the C1 fine structure data.

REFERENCES

Abel, N. P., Brogan, C. L., Ferland, G. J., O’Dell, C. R., Shaw, G., & Troland, T. H. 2004, \textit{ApJ}, 609, 247
Abrahamsson, E., Krems, R. V., & Dalgarno, A. 2007, \textit{ApJ}, 654, 1171
Anders, E., & Grevesse, N. 1989, \textit{Geochim. Cosmochim. Acta}, 53, 197
Carswell, R. F., Hilliard, R. L., Strittmatter, P. A., Taylor, D. J., & Weymann, R. J. 1975, \textit{ApJ}, 196, 351
Carswell, R. F., Jorgenson, R. A., Wolfe, A. M., & Murphy, M. 2010, \textit{MNRAS}, submitted
Cui, J., Bechtold, J., Ge, J., & Meyer, D. M. 2005, \textit{ApJ}, 633, 649
Desauges-Zavadsky, M., Calura, F., Prochaska, J. X., D’Oorio, S., & Matteucci, F. 2004, \textit{A&A}, 416, 79
Draine, B. T., & Bertoldi, F. 1996, \textit{ApJ}, 468, 269
Haardt, F., & Madau, P. 1996, \textit{ApJ}, 461, 20
Hirashita, H., & Ferrara, A. 2005, \textit{MNRAS}, 356, 1529
Hollenbach, D. J., & McKee, C. F. 1979, \textit{ApJS}, 41, 555
Jenkins, E. B., & Shaya, E. J. 1979, \textit{ApJ}, 231, 55
Jenkins, E. B., & Tripp, T. M. 2001, \textit{ApJ}, 137, 297
