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COLD NEUTRAL GAS IN A $z = 4.2$ DAMPED Lyα SYSTEM: FUEL FOR STAR FORMATION

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ABSTRACT

We discuss interstellar temperature determinations using the excitation equilibrium of the ^2P levels of Si II and C II. We show how observations of the $^2P_{3/2}$ fine-structure levels of Si II and C II (which have significantly different excitation energies, corresponding to ∼413 and 92 K, respectively) can be used to limit gas kinetic temperatures. We apply this method to the $z = 4.224$ damped Lyα system toward the quasar PSS 1443+27. The lack of significant absorption out of the Si II $^2P_{3/2}$ level and the presence of very strong C II $^2P_{3/2}$ provide an upper limit to the temperature of the C II*–bearing gas in this system. Assuming a solar Si/C ratio, the observations imply a 2 σ limit $T < 954$ K for this absorber; a supersolar Si/C ratio gives stricter limits, $T < 524$ K. The observations suggest the presence of a cold neutral medium; such cold gas may serve as the fuel for star formation in this young galaxy.

Subject headings: galaxies: evolution — ISM: atoms — ISM: evolution — quasars: absorption lines

1. INTRODUCTION

High-redshift damped Lyα (DLA) systems are the highest column density class of QSO absorption lines. Defined by $\log N(\mathrm{H\,I}) \geq 20.3$ (Wolfe et al. 1986), these systems are thought to trace the interstellar medium (ISM) of high-redshift galaxies. Dedicated surveys over the past two decades have helped trace the global properties of high-redshift DLA systems, including their contribution to the cosmological baryon density (Storrie-Lombardi & Wolfe 2000; Prochaska & Herbert-Fort 2004), their chemical enrichment (e.g., Prochaska et al. 2003), their dust content (e.g., Pettini et al. 1994), and their molecular fraction (Ledoux et al. 2003). These studies have demonstrated that the DLA systems have a baryonic mass density comparable to the mass density of modern galaxy disks, that the metallicity of high-z DLA systems is slowly increasing, and that the majority of DLA sight lines have low dust-to-gas ratios and molecular fractions.

Understanding the detailed physics of the ISM in DLA systems is an important step in understanding high-redshift galaxies in general. Wolfe et al. (2003b) have constructed detailed models for the thermal equilibrium of the ISM in a set of DLA systems, calculating the heating rate experienced by the gas due to the ultraviolet emission from young hot stars. They used observations of absorption out of the $^2P_{3/2}$ level of C II (hereafter C II*)—a direct indicator of the cooling rate through [C II] 158 μm emission (Pottasch et al. 1979)—to infer the actual heating rate experienced by the gas (assuming thermal equilibrium). Their comparison of the inferred and calculated heating rates suggests that DLA systems harbor significant star formation.

The models of Wolfe et al. (2003a, 2003b) required that the observed C II* in DLA systems arise in a cold neutral medium (CNM), i.e., in gas with temperatures $T \lesssim 1000$ K; their warm neutral medium (WNM) models give star formation rates that violate observations of the bolometric background. The detection of H_2 absorption in some high-z DLA systems is further evidence that at least some of these systems contain a CNM (Ledoux et al. 2003; Hirashita & Ferrara 2005). However, such temperatures are at odds with 21 cm absorption studies; all of the $z \gtrsim 3$ DLA systems that were searched for 21 cm absorption show $T_s \gtrsim 1400$ K (2 σ; Kanekar & Chengalur 2003). Wolfe et al. (2003a) argue that this discrepancy is likely due to the differing properties of the sight lines probed by the optical background sources and by the more extended radio sources.

In this Letter we present a method for determining the kinetic temperature of interstellar matter based solely on basic atomic physics. Our method compares the excitation of the upper $^2P_{3/2}$ fine-structure levels in Si II and C II, which have excitation energies that differ by a factor of 4. We describe our approach in § 2. We apply this technique to the $z_{\mathrm{abs}} \approx 4.224$ DLA system toward the quasar PSS 1443+27 in § 3, demonstrating that this DLA system contains a substantial reservoir of cold gas. Finally, we discuss the implications of this temperature determination in § 4.

2. DETERMINING GAS TEMPERATURES FROM $N(\mathrm{Si\,II^*})$ AND $N(\mathrm{C\,II^*})$

In this section we discuss how analysis of the ^2P fine-structure excitation in Si II and C II can be used to limit interstellar kinetic temperatures. Srianand & Petitjean (2000) have used a similar analysis to limit temperatures and densities in an associated absorber. Silva & Viegas (2002, hereafter SV) give a detailed summary of the excitation equilibrium of fine-structure lines in DLA systems.

We treat the excitation of the ^2P fine-structure states as a two-level atom.[4] The equilibrium ratio of the densities in the upper and lower levels (Spitzer 1978), n_2 and n_1, respectively, is

$$\frac{n_2}{n_1} = \frac{B_{12} u_{\nu_{12}}(z) + \Gamma_{12} + \sum_k n_k \gamma_{12}^k}{A_{21} + B_{21} u_{\nu_{12}}(z) + \Gamma_{21} + \sum_k n_k \gamma_{21}^k}\,. \tag{1}$$

The quantities A_{21}, B_{21}, and B_{12} are the familiar Einstein transition probabilities. The energy density of the cosmic micro-

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[4] This is appropriate given the temperatures of the ISM probed by low-ionization absorption lines ($T \ll 30{,}000$ K).

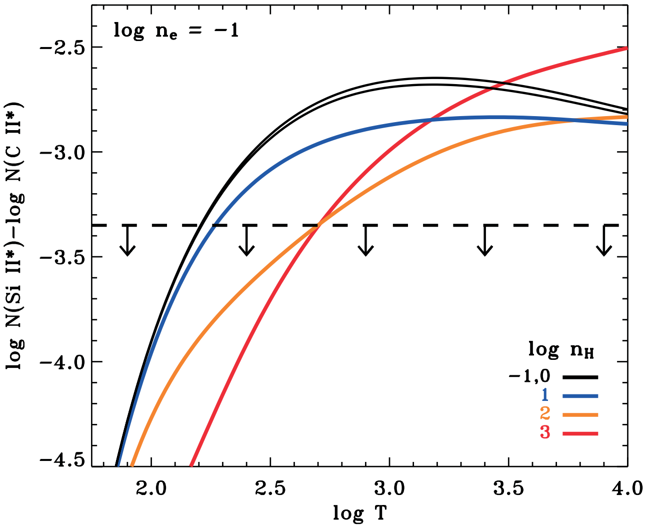

FIG. 1.—Predicted N(Si II*)/N(C II*) for a DLA system at $z \sim 4.22$ with $\log n_e = -1$ and a large range of hydrogen densities. The dashed line represents the 2 σ upper limits to N(Si II*)/N(C II*) for the DLA system toward PSS 1443+27. Electrons generally dominate the collisional excitation of Si II and C II ($\gamma^e_{12} \gg \gamma^{\rm H}_{12}$). Although at very low values of $x \equiv n_e/n_{\rm H}$ (*bottom curves*), H I collisions become important. The change in slope of the lowest x curves is due to the larger relative importance of H I in collisional excitations of C II than in Si II (compare Figs. 3 and 7 of SV) and the differing temperature dependence for $\gamma^{\rm H}_{12}$. The ratios of the $^2P_{3/2}$ to $^2P_{1/2}$ levels of C II and Si II can be used to constrain $n_{\rm H}$ and x.

wave background, $u_{\nu_{12}}(z)$, for direct excitation of the transitions is calculated assuming a standard cosmology; i.e., $T_{\rm CMB} = T_0(1+z)$, where $T_0 = 2.725$ K (Mather et al. 1999). The fluorescent rates $\Gamma_{12} = \Gamma_{21} = 0$ because of the great opacity of the ground-state transitions of interest (Sarazin et al. 1979; see Wolfe et al. 2003b). The summations describe excitations and de-excitations with collision partners k ($=e^-$, p^+, and H^0), where n_k is the particle density of each partner, and γ^k_{12} and γ^k_{21} are the Maxwellian-averaged collision rate coefficients for excitation and de-excitation. The collision rates are related to one another and to $\Omega^k_{12}(T)$, the collision strength (Spitzer 1978), by

$$\gamma^k_{12} \propto \gamma^k_{21} \exp{(-kT_{12}/kT)} \propto \Omega^k_{12}(T) T^{-1/2} \exp{(-kT_{12}/kT)}, \tag{2}$$

where kT_{12} is the energy of the $^2P_{3/2}$ level above the ground state and T is the gas kinetic temperature. We adopt atomic data from the same sources as SV throughout.

The column density of material in the $^2P_{3/2}$ level of C II is

$$N(\text{C II}^*) \approx \int \frac{n_{\text{C II}^*}}{n_{\text{C II}}} A(\text{C}) n_{\rm H}\, ds, \tag{3}$$

where A(C) is the gas-phase abundance of carbon, $n_{\rm H}$ is the density of neutral hydrogen, ds is the differential path length along the line of sight, and the $n_{\text{C II}^*}/n_{\text{C II}}$ ratio is a function of four quantities: $z_{\rm abs}$, $n_{\rm H}$, $x \equiv n_e/n_{\rm H} \approx n_p/n_{\rm H}$, and T (eq. [1]). We have assumed $n_{\text{C II}} \approx n_{\rm C} \equiv A(\text{C}) n_{\rm H}$, consistent with the limits on C I in DLA systems (see Fig. 12 of Wolfe et al. 2003a). A similar expression applies for Si II*. The column densities of C II* and Si II* are therefore density- and excitation-weighted integrals over path length.

TABLE 1
PSS 1443+27 DAMPED Lyα SYSTEM PROPERTIES[a]

Quantity	Value
$z_{\rm abs}$	4.2240
log N(H I)	20.80 ± 0.10
[Fe/H]	−1.10 ± 0.11
log N(Si II)	>15.43
log N(Fe II)	15.20 ± 0.06
log N(C I)	13.37 ± 0.09
log N(C II*)	>14.71
log N(Si II*)	<11.24 (2 σ)
log [N(Si II*)/N(C II*)]	<−3.47 (2 σ)

[a] N(H I), [Fe/H], and column densities, with the exception of Si II*, are from Prochaska et al. (2001).

To understand the usefulness of Si II* and C II* to limit gas temperatures, imagine that the excitation of the $^2P_{3/2}$ states were only due to electron collisions, and de-excitation due to spontaneous emission. In this case N(Si II*)/N(C II*) $\propto$ [A(Si)/A(C)] × $[\Omega^e_{12}(T)_{\rm Si}/\Omega^e_{12}(T)_{\rm C}] \exp{[-(T^{\rm Si}_{12} - T^{\rm C}_{12})/T]}$; i.e., the ratio is only a function of temperature and the Si/C ratio. Figure 1 shows the N(Si II*)/N(C II*) ratio as a function of temperature, including all of the terms in equation (1), for several densities at $z \sim 4.2$ assuming [Si/C] $= 0$.[5] N(Si II*)/N(C II*) varies slowly with temperature for $T \gtrsim 1000$ K (for all but the highest densities) and more strongly at lower temperatures. The sensitivity to density is modest, especially for low x, because the populations of the $^2P_{3/2}$ levels of Si II and C II depend on density in a similar manner. We use the ratio of the $^2P_{3/2}$ to $^2P_{1/2}$ levels of C II and Si II to constrain the allowable range of densities.

Gas at $T \lesssim 1000$ K produces ratios log [N(Si II*)/N(C II*)] $\lesssim -2.8$; the corresponding optical depth ratio of the 1264.738 Å line of Si II* to the typically unresolved 1335.663 and 1335.708 Å doublet of C II* is $\tau(1264)/\tau(1335) \lesssim 0.015$ (f-values from Morton 2003). Thus, the use of this ratio to distinguish cool from warm temperatures requires large C II* optical depths and a good signal-to-noise ratio (S/N) at Si II*. Observations of N(Si II*)/N(C II*) will allow a range of parameters $n_{\rm H}$, x, and T, which apply to the C II*–bearing gas. However, the maximum allowable temperature can be low if the limits on N(Si II*)/N(C II*) are low.

3. APPLICATION TO THE $z = 4.224$ DAMPED Lyα SYSTEM TOWARD PSS 1443+27

Prochaska et al. (2001) present high-resolution ($R \sim 40{,}000$), high S/N observations of the $z = 4.224$ DLA system toward the quasar PSS 1443+27 using the High Resolution Echelle Spectrometer (HIRES; Vogt et al. 1994) on the Keck I 10 m telescope. The properties of this DLA system are summarized in Table 1. Due to its redshift and relatively strong metal lines, column densities can only be measured for a few species. Table 1 gives a measurement of Fe II (from the 1611.2 Å transition) and meaningful limits on C II*, Si II, and Si II*. All but the last of these are from Prochaska et al. (2001).

Figure 2 shows the HIRES spectrum at the expected location of Si II* in this absorber, including our fitted continuum. Our limit to Si II* was determined using an empirically measured signal-to-noise ratio (following Sembach & Savage 1992) and includes continuum placement uncertainties. Figure 3 shows the normalized profiles of Si II* and C II*. Also shown are models for the expected Si II* absorption for a canonical WNM (with $n_{\rm H} = 1$ cm^{-3}, $x = 0.1$, and $T = 8000$ K) and CNM (with

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[5] [X/Y] ≡ log N(X)/N(Y) − log $(\text{X/Y})_\odot$.

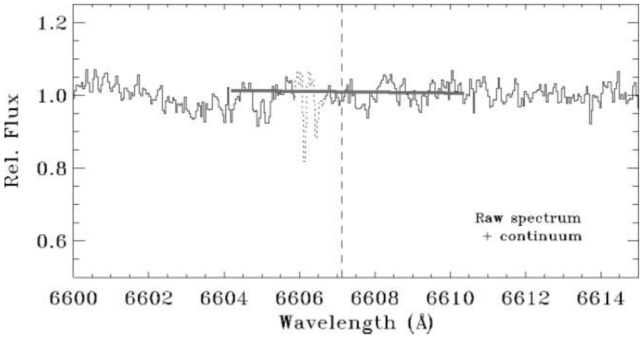

FIG. 2.—Observed spectrum near the expected position of Si II* for the $z = 4.224$ DLA system toward PSS 1443+27 (shown by the dashed line). The thick gray line represents our fitted continuum. The dotted region denotes the location of two poorly subtracted sky emission lines, which cause the narrow depressions in this region of the spectrum.

$n_{\rm H} = 10$ cm^{-3}, $x = 10^{-3}$, and $T = 80$ K). The models are derived by scaling the C II* profile by the amount predicted using equations (1) and (3) and assuming [Si/C] = 0. The hypothesis that C II* absorption toward PSS 1443+27 arises in a canonical WNM is not consistent with the observations.

To limit T, we calculate the excitation balance of the fine-structure levels of Si II and C II for densities $-4 \leq \log n_e \leq +2$ and $-2 \leq \log n_{\rm H} \leq +3$ and temperatures $1.5 \leq \log T \leq 4.5$. We compare these calculations with our observational limits for N(Si II*)/N(C II*), N(C II*)/N(C II), and N(Si II*)/N(Si II) to constrain the physical properties ($n_{\rm H}$, x, and T) of the gas in the C II*–bearing gas.[6]

The allowable range of physical conditions in the PSS 1443+27 DLA system then depends on the Si/C and C/Fe ratios, which are used for determining the expected N(Si II*)/N(C II*) and N(C II*)/N(C II), respectively. C II is rarely measurable in DLA systems because of saturation effects; we estimate N(C II) from N(Fe II) (Table 1) with an assumed abundance ratio. As a fiducial, we adopt the solar system ratios from Grevesse & Sauval (1998): $\log{\rm (C/Fe)}_\odot = +1.02$ and $\log{\rm (Si/C)}_\odot = -0.96$. This gives $\log N$(C II) $= 16.22 \pm 0.06$. Nucleosynthetic effects are unlikely to modify the C/Fe ratio, as a roughly solar value is found in low-metallicity Milky Way stars (e.g., Carretta et al. 2000). However, nucleosynthetic effects could enhance α-element abundances, leading to high Si/C ratios (see, e.g., Prochaska 2003). In one case in which the C II measurements may be reliable, D'Odorico & Molaro (2004) find $\log N$[(Si II)/N(C II)] $= -0.74 \pm 0.07$ and $\log N$[(C II)/N(Fe II)] $= +1.25 \pm 0.12$ (assuming the Fe II column from Lu et al. 1996). This implies [C/Fe] = +0.23 and [Si/C] = +0.22 compared with our adopted solar system abundances. However, the overall metallicity of this absorber is [Si/H] = −1.72, which is significantly lower than the metallicity of the DLA system studied in this work.

The presence of dust will raise the C/Fe ratio because of differential depletion. The depletion of Fe in DLA systems is typically modest, similar to the "halo" and "disk-halo" clouds in the Milky Way (Savage & Sembach 1996) with [Fe/H] $\gtrsim -0.9$.[7] For diffuse clouds in the Milky Way, Sofia et al. (2004) find [C/H] ~ -0.3. Thus, we expect [C/Fe] $\lesssim +0.6$. In low-depletion Milky Way clouds, and by extension DLA systems,

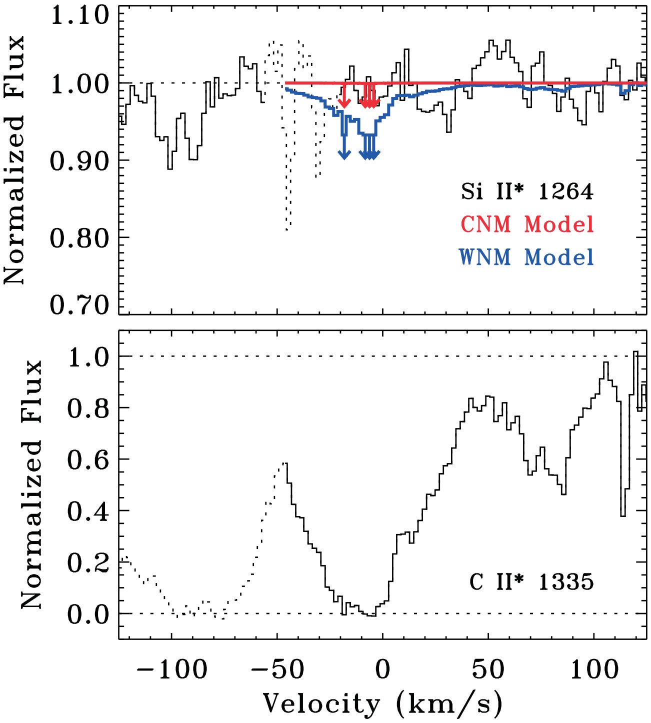

FIG. 3.—Normalized Si II* and C II* profiles for the $z = 4.224$ DLA system toward PSS 1443+27. Included in the panel showing Si II* are two predicted Si II* profiles derived from the observed C II* profile assuming standard WNM (*blue histogram*, with $n_{\rm H} = 1$ cm^{-3}, $x \equiv n_e/n_{\rm H} = 0.1$, and $T = 8000$ K) and CNM (*red histogram*, with $n_{\rm H} = 10$ cm^{-3}, $x = 10^{-3}$, and $T = 80$ K) properties. These models assume [Si/C] = 0. The arrows denote regions of definite saturation in the C II* profile. The dotted region in the Si II* profile denotes the location of two poorly subtracted sky emission lines.

Si is likely not depleted much differently from C, and we assume [Si/C] = 0. The small number of species for which measurements are possible in the DLA system toward PSS 1443+27 makes it difficult to judge the degree of Fe depletion. Moderate depletion is suggested by [Si/Fe] > +0.17, but this could also result from α-enhanced abundances.

We give temperature limits for the C II*–bearing gas in the $z \sim 4.224$ DLA system toward PSS 1443+27 for six different abundance assumptions in Table 2. The first three assume [Si/C] = 0 with [C/Fe] = +0.0, +0.3, and +0.6, allowing for modest levels of depletion. The next three assume [Si/C] = +0.3, i.e., α-enhanced abundances (see Prochaska 2003). We note that the model in which [Si/C] = [C/Fe] = 0 is not self-consistent, since scaling both Si II and Fe II by solar abundances gives inconsistent values for the C II column density.

The highest limit is $T < 954$ K, assuming [C/Fe] = +0.6

TABLE 2

TEMPERATURE LIMITS FOR $z = 4.22$ DAMPED SYSTEM

Model	[Si/C]	[C/Fe]	T (K)	$\log n_{\rm H}$[a]
1 ……	+0.0	+0.0	<478	1.44
2 ……	+0.0	+0.3	<724	1.04
3 ……	+0.0	+0.6	<954	0.56
4 ……	+0.3	+0.0	<416	1.46
5 ……	+0.3	+0.3	<436	1.14
6 ……	+0.3	+0.6	<524	0.64

[a] Hydrogen density giving maximum allowed temperature in each model.

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[6] These three physical quantities are coupled in the calculations. A wide range of T-dependent x- and $n_{\rm H}$-values are allowable, and only T is stringently constrained in our analysis.

[7] The intrinsic gas+dust abundance in the Milky Way is [Fe/H] ≈ 0. Thus, unlike the case in DLA systems, the subsolar gas-phase Fe/H quoted here is due entirely to depletion into dust grains.

and [Si/C] = 0. This is likely an extreme assumption for the C/Fe ratio. The highest temperature limit for α-enhanced abundances, which we prefer because of the distribution of [Si/Fe] at very low metallicities (where dust depletion effects are likely small; see Prochaska 2003), is $T < 524$ K. Temperatures above 1400 K, consistent with T_s limits for the $z \geq 2.9$ DLA systems observed at 21 cm (Kanekar & Chengalur 2003), require [C/Fe] $\gtrsim +0.75$ to $+0.8$ for both solar and α-enhanced abundances. We feel this is inconsistent with our knowledge of differential depletion in the Milky Way and DLA systems.

4. DISCUSSION

We have presented a method for limiting gas temperatures in the ISM of galaxies through measurements and analysis of the $^2P_{3/2}$ fine-structure levels of Si II and C II. We have applied this method to limit the properties of the C II*–bearing gas in the $z = 4.224$ DLA system toward PSS 1443+27. We rule out the hypothesis that the C II* absorption arises in a WNM. Our conservative temperature limit for this gas is $T \lesssim 954$ K; we obtain stricter temperature limits if [Si/C] > 0 or [C/Fe] ≈ 0: $T \lesssim 524$ K. The detection of a CNM (Wolfire et al. 1995) in a high-redshift DLA system is significant: while the gas seen in this DLA is likely not associated with the dense star-forming clouds, our result demonstrates that the physical conditions of the ISM in this system do not preclude the existence of cold material, including, in principle, the dense clouds from which stars could form.

The detection of a CNM in the $z = 4.224$ absorber toward PSS 1443+27 is the first detection at such a large redshift. We stress that our measurements allow a WNM as part of a multiphase medium toward PSS 1443+27, but the majority of the C II* cannot come from warm material.[8] The existence of CNM material may be a feature of many high-z DLA systems, as suggested by Wolfe et al. (2003a, 2003b). While $z \lesssim 2$ H I 21 cm absorption-line measurements suggest the presence of cold H I in DLA systems, no 21 cm absorption has been found in DLA systems with $z \gtrsim 3$ (Kanekar & Chengalur).[9] We note, however, that at least three $z > 2.5$ DLA systems show H_2 absorption (Ledoux et al. 2003), indicating the presence of cold gas (Hirashita & Ferrara 2005). Searching for H_2 toward PSS 1443+27 might be difficult because of the strength of the Lyα forest at $z \sim 4$. In the future we will apply our method for determining gas kinetic temperatures to DLA systems for which 21 cm and H_2 measurements have been attempted.

We note that the DLA system toward PSS 1443+27 may not be typical. It shows a high metallicity ([Si/H] $\gtrsim -1$), especially compared with other $z > 4$ DLA systems (Prochaska et al. 2003). Furthermore, we chose this DLA system for this experiment because it has very strong C II*. It has the highest C II*/H I ratio measured, some +0.6 dex above the next highest (the $z = 1.92$ DLA system toward Q2206−19; Wolfe et al. 2004). The intensity of radiation in this DLA system calculated following Wolfe et al. (2004) is higher than all other systems. Although the fuel for star formation may be present in this DLA system, no optical counterpart to this DLA system has been identified in deep ground-based and *Hubble Space Telescope* images of PSS 1443+27 (Prochaska et al. 2002; L. Storrie-Lombardi 2004, private communication).

The method presented here will be discussed further, and temperature limits given for a larger number of DLA systems, in J. C. Howk et al. (2005, in preparation). We note that the use of the relative populations of the $^2P_{3/2}$ levels of Si II and C II may also be useful for constraining temperatures in Milky Way gas.

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[8] We have tested the effects of multiphase absorbers on our technique, with as much as half of the ground-state ions arising in a WNM. We find that there is very little impact on the derived maximum temperatures (J. C. Howk et al. 2005, in preparation).

[9] Only six $z > 2.9$ DLA systems have been observed; PSS 1443+27 has not been searched for 21 cm absorption.

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