

H₂, C I, METALLICITY, AND DUST DEPLETION IN THE $z = 2.34$ DAMPED Ly α ABSORPTION SYSTEM TOWARD QSO 1232+0815¹

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Received 2000 October 2; accepted 2000 November 7; published 2001 January 16

ABSTRACT

We report the detection of strong molecular hydrogen (H₂) absorption lines in the $z = 2.34$ damped Ly α absorber (DLA) toward QSO 1232+0815. This is the second detection in our survey for high-redshift molecules. The new ultraviolet spectrum of the QSO 1232+0815 at 0.9 Å resolution, taken with the Multiple Mirror Telescope Blue Channel Spectrograph, shows the $v = 0-0$ up to 10-0 Lyman bands and also the Werner $v = 0-0$ band of H₂ associated with the $z = 2.34$ DLA. We have estimated the total H₂ column density in this system. It ranges from $\approx 3 \times 10^{19} \text{ cm}^{-2}$ to $\approx 3 \times 10^{17} \text{ cm}^{-2}$ depending on the Doppler parameters, $b = 6$ or 10 km s⁻¹. Based on the best fit with $b = 6$ km s⁻¹, the estimated kinetic temperature is $T_k \approx 80$ K. The measurements of the abundance of zinc and iron in the same DLA show that the metallicity measured by the relatively undepleted element zinc is $[\text{Zn}/\text{H}] = -0.86$, while the relative abundance ratio $[\text{Fe}/\text{Zn}]$ is -1.04 , indicating dust depletion. Combining our work with previous results on H₂ and relative heavy-element depletion, we find that there is a correlation between them, which suggests that the formation of H₂ on dust grains is perhaps the dominant formation process in high-redshift DLAs. Detections of strong absorption from the ground and excited states of neutral carbon (C I) in the $z = 2.34$ DLA are also presented. The excitation temperature between the two fine-structure levels of C I is 15.7 ± 3.5 K, an upper limit for the cosmic microwave background radiation temperature at $z = 2.34$. This value is consistent with the prediction by the standard big bang cosmology.

Subject headings: cosmic microwave background — dust, extinction — early universe — galaxies: abundances — ISM: molecules — quasars: absorption lines — quasars: individual (QSO 1232+0815)

1. INTRODUCTION

Damped Ly α quasar absorption-line systems dominate the cosmological mass density of neutral gas in the universe and trace the bulk of material available for star formation at high redshifts (Lanzetta 1993). Therefore, they are important for studying the physical and chemical properties of normal galaxies at high redshifts through observations of molecular gas, metallicity, and dust depletion. Previous works (e.g., Pettini et al. 1994, 1997; Lu et al. 1996) have extensively studied the abundances and the plausible dust depletion in the damped Ly α absorbers (DLAs), which are helpful for understanding the chemical evolution of these galaxies. Recent imaging studies of galaxies in the Hubble Deep Field using the *Hubble Space Telescope* (HST) and of galaxies associated with the DLAs using ground-based infrared telescopes provide further information on the star formation history of galaxies in the early universe (e.g., Steidel et al. 1996; Lowenthal et al. 1997; Madau 1998; Bechtold et al. 1998). However, little is known about molecules in these high-redshift quasar DLAs. For most of the DLAs with modest star formation rates, the sensitivity of the present millimeter and submillimeter telescopes is not sufficient to detect molecular gas (Ge et al. 1997b).

Molecules, especially molecular hydrogen (H₂), can be studied through quasar absorption-line observations. H₂ is the most abundant molecule in the universe. It shows strong UV absorption transitions in the interstellar clouds of the local uni-

verse (e.g., Savage et al. 1977; Shull et al. 2000). For $z > 1.8$, the UV lines from H₂ are redshifted into optical wavelengths. Therefore, they can be studied by ground-based telescopes. H₂, because of its rich structure (e.g., Morton 1975), potentially provides an extremely powerful probe of the physical and chemical conditions in DLAs at high redshifts. However, the study of H₂ absorption lines at high redshifts has been very difficult because the blending of the H₂ absorption lines with numerous Ly α forest lines significantly limits the detection sensitivity.

Previous to this work, H₂ absorption was reported in two damped Ly α absorbers, the $z = 2.811$ DLA toward Q0528–250 ($z_{\text{em}} = 2.77$; Foltz, Chaffee, & Black 1988) and the $z = 1.97$ DLA toward Q0013–004 ($z_{\text{em}} = 2.08$; Ge & Bechtold 1997). Here we report detection of H₂, C I, Zn II, and other metal absorption lines in another DLA at $z = 2.34$ toward quasar Q1232+0841 (Ge & Bechtold 1999).

2. OBSERVATIONS

Spectroscopic observations of Q1232+0815 were obtained with the Multiple Mirror Telescope (MMT) and the Blue Channel Spectrograph during the spring of 1997 using an 832 g mm⁻¹ grating blazed at 3900 Å in second order and a 1200 g mm⁻¹ grating blazed at 4800 Å in first order. A Loral 3072 × 1024 CCD was used to record the data. A 1" × 180" slit was used for both 832 and 1200 g mm⁻¹ gratings to give a resolution of 0.9 and 1.4 Å, respectively, as measured from the comparison lamp lines. The data were recorded in several windows to cover important absorption lines from the key species in the $z = 2.34$ DLA, such as H₂, C I, Zn II, Fe II, Si II, and S II, and were reduced in the standard way using IRAF. Figure 1 presents part of the UV spectrum of

¹ Observations here were obtained with the Multiple Mirror Telescope, a joint facility of the University of Arizona and the Smithsonian Institution.

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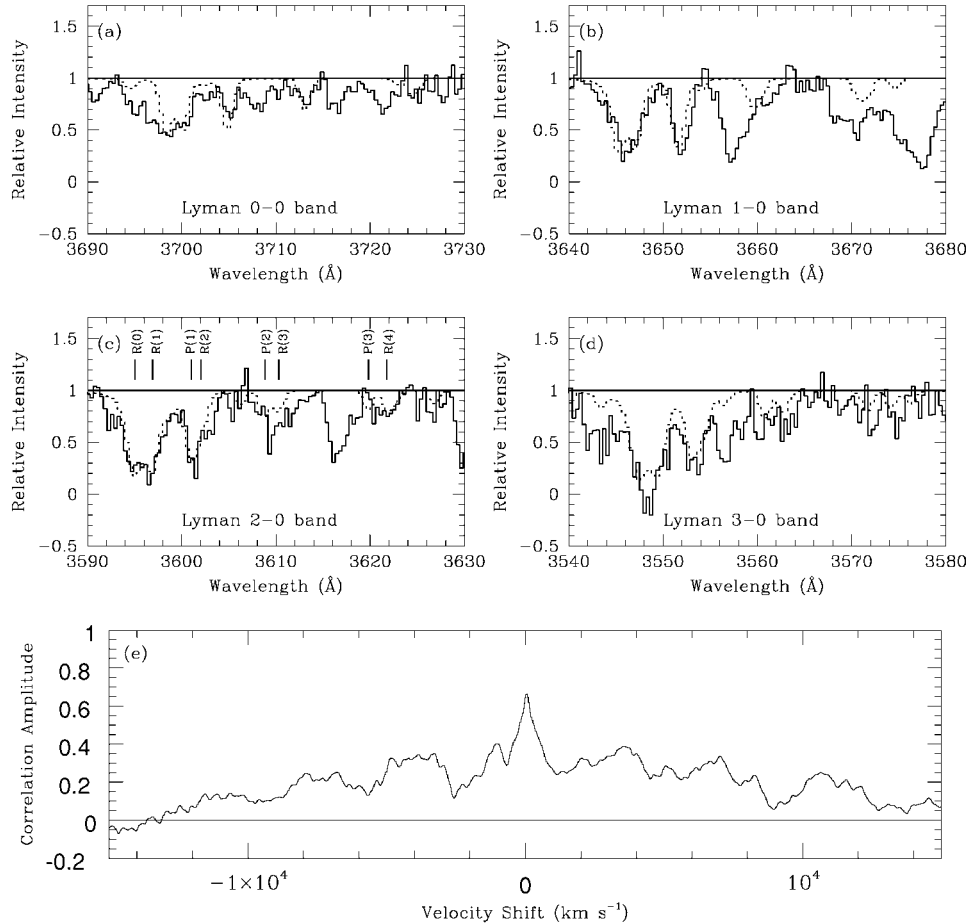


FIG. 1.—(a–d) Portion of the Q1232+0815-normalized spectrum showing the Lyman $\nu = 0-0$, $1-0$, $2-0$, and $3-0$ absorption bands associated with the $z = 2.34$ DLA. The synthetic H_2 absorption lines (dotted line) are overlotted. For the $\nu = 2-0$ band, the wavelengths of the $J \leq 4$ transitions [$R(0)$, $R(1)$, $P(1)$, $R(2)$, $P(2)$, $R(3)$, $P(3)$, and $R(4)$] are marked. (e) Cross-correlation between the QSO spectrum and the synthetic H_2 absorption-line spectrum. The peak at the zero velocity has the largest amplitude in the testing range from $-30,000$ to $30,000 \text{ km s}^{-1}$.

Q1232+0815 containing H_2 absorption. Figure 2 shows spectra at longer wavelengths containing absorption lines, $\text{C I } \lambda 1656$, $\text{Zn II } \lambda 2026$, and $\text{Fe II } \lambda 1608$. The weak absorption lines from $\text{C I } \lambda 1656$, $\text{Zn II } \lambda 2026$, and $\text{Si II } \lambda 1808$, as well as the relatively weak absorption lines from $\text{Fe II } \lambda 1608$ and $\text{S II } \lambda 1253$, are clearly present in the spectrum. However, the lines $\text{Cr II } \lambda 2056$, $\lambda 2062$, and $\lambda 2066$ are not detected because they are blended with the strong telluric O_2 absorption band.

3. RESULTS

The spectral region containing the H_2 Lyman $\nu = 0-0$ up to $10-0$ bands and the Werner $0-0$ band for this DLA has been published in a previous review paper (Ge & Bechtold 1999). Figure 1 shows the expanded portion of Lyman $\nu = 0-0$ to $4-0$ bands. A simulated H_2 absorption spectrum is plotted as a dotted line for comparison. The wavelengths of the $J \leq 4$ transitions in the $2-0$ band are marked. There is remarkable agreement between the two spectra despite the presence of $\text{Ly}\alpha$ forest lines. However, since the H_2 absorption lines are possibly blended with the crowded $\text{Ly}\alpha$ forest lines in the quasar spectrum, the observed configuration of H_2 lines in the $z = 2.34$ DLA might be the result of chance coincidence with the $\text{Ly}\alpha$ forest lines. To check the presence of H_2 , we performed a cross-correlation test using the FXCOR program in IRAF (see Tonry & Davis 1979, § III, for details; Foltz et al. 1988; Ge & Bech-

told 1997). The cross-correlation was conducted between the observed quasar spectrum at $3300-3800 \text{ \AA}$ and the simulated H_2 absorption spectrum at the same wavelength region. The cross-correlation function was computed for lags in the range $-30,000 \text{ km s}^{-1} \leq \Delta v \leq 30,000 \text{ km s}^{-1}$. The result shows a very strong, sharp peak with the correlation amplitude of 0.66 at the zero velocity shown in Figure 1, corresponding to redshift $z = 2.3376$, indicating the presence of the H_2 absorption lines. The detection of the H_2 absorption lines has been recently confirmed by the Very Large Telescope (VLT) echelle spectroscopy at higher spectral resolution (Petitjean, Srianand, & Ledoux 2000).

The total H_2 column density, $N(\text{H}_2) \approx 3.1 \times 10^{19} \text{ cm}^{-2}$, was derived from the best fit of a synthetic H_2 spectrum to the observed one as shown in Figure 1. The Doppler parameter, $b \approx 6 \text{ km s}^{-1}$, adopted in the H_2 spectrum synthesis is derived from a curve of growth based on 22 absorption lines from the $J = 2, 3$, and 4 rotational levels in the H_2 Lyman and Werner bands. Based on this b -value, the populations on different rotational levels are derived as shown in Table 1, which also includes the derived excitation temperatures between the different rotational levels. The measured $T_{01} = 80 \pm 19 \text{ K}$ value is in the range of typical values of the Milky Way, LMC, and SMC diffuse clouds (Savage et al. 1977; Shull et al. 2000) and also similar to the $z = 1.97$ DLA toward QSO 0013–004 (Ge

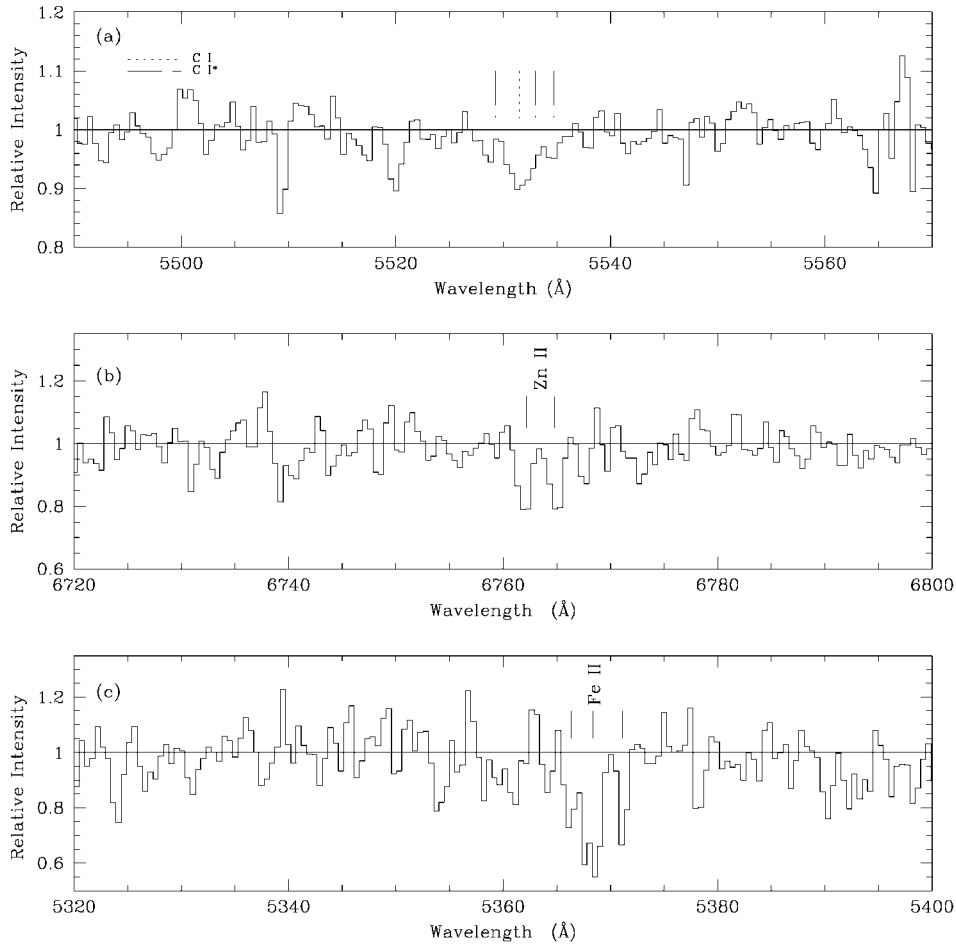


FIG. 2.—(a) Part of the spectrum of QSO 1232+0815 showing absorption lines from the C I multiplet 2. The expected positions of the ground and first excited states are marked. (b) Q1232 spectrum showing absorption lines from Zn II λ 2026. Two velocity components ($z = 2.3375$ and 2.3388) are identified. (c) Q1232 spectrum showing absorptions from Fe II λ 1608. Three velocity components are associated with the DAL ($z = 2.3363$, 2.3376 , and 2.3393).

& Bechtold 1997). $T_{02} = 63^{+5}_{-3}$ K is also in the range of the average value for the Milky Way clouds. The excitation temperatures $T_{\text{ex}} = 170\text{--}800$ K for higher J are similar to those of Milky Way absorption clouds (Spitzer, Cochran, & Hirshfeld 1974; Shull et al. 2000).

The observed damped Ly α absorption spectrum was fitted to simulated line profiles in order to measure the total neutral hydrogen column density $N(\text{H})$. The derived $N(\text{H I}) = 8.0(\pm 1.0) \times 10^{20} \text{ cm}^{-2}$, and the Doppler parameter $b_{\text{H I}} = 50 \text{ km s}^{-1}$. The redshift for the best Voigt profile fitting to the

damped Ly α absorption is $z_{\text{H I}} = 2.3384$. The neutral hydrogen absorption redshift is slightly higher than the H₂ absorption redshift, which probably indicates that H₂ is only associated with one of the H I clouds in the DLA. The fractional H₂ abundance, given by $f = 2N(\text{H}_2)/[2N(\text{H}_2) + N(\text{H I})] \approx 0.07$ if all H I is associated with the cloud containing H₂, is similar to that of the $z = 1.97$ absorber toward Q0013–004 (Ge & Bechtold 1997).

There are at least three velocity components, identified from the metal absorption lines associated with the $z = 2.34$ DLA. The average redshifts are 2.3363, 2.3374, and 2.3389. H₂ absorption is therefore probably associated with the $z = 2.3374$ metal line system, while the C I absorption seems to be associated with the $z = 2.3389$ metal line component.

The detections of Zn II and Fe II allow us to measure the abundance and dust depletion in this system. In the interstellar medium of the Milky Way, zinc shows little affinity for interstellar dust (e.g., Jenkins 1987), and it traces iron to about $[\text{Fe}/\text{H}] \sim -2.5$ (Wheeler, Sneden, & Truran 1989). Iron, just like chromium, is an element heavily depleted on to dust grains in the interstellar medium (Jenkins 1987). Therefore, the depletion of Fe relative to Zn is very useful for tracing dust. Since the spectral resolution is not sufficient to resolve the profiles of the metal lines. The abundances are derived indirectly through the curve-of-growth technique. A best-fit b -value of

TABLE 1
H₂ COLUMN DENSITIES AND EXCITATION
TEMPERATURES IN THE $z = 2.34$ DLA

Level	N^a (cm^{-2})	T_{ex} (K)	J_{ex}
$J = 0$	$1.5(\pm 0.5) \times 10^{19}$
$J = 1$	$1.6(\pm 0.6) \times 10^{19}$	80^{+19}_{-19}	0–1
$J = 2$	$2.3^{+1.2}_{-0.5} \times 10^{16}$	$63^{+5.0}_{-3.1}$	0–2
$J = 3$	$5.0^{+1.7}_{-1.5} \times 10^{15}$	171^{+198}_{-21}	2–3
		$95^{+37}_{-5.0}$	1–3
$J = 4$	$1.9^{+4.2}_{-0.7} \times 10^{15}$	380^{+278}_{-52}	2–4
$J = 5$	$\leq 1.0 \times 10^{15}$	< 397	2–5
$J = 6$	$\leq 1 \times 10^{15}$	< 725	2–6
$J = 7$	$\leq 1 \times 10^{15}$	< 764	2–7

^a 2σ upper limits are given for $J = 5, 6$, and 7 .

TABLE 2
ABUNDANCES IN THE $z = 2.34$ DLA SYSTEM^a

[Zn/H]	[Fe/H]	[S/H]	[Si/H]	[Fe/Zn]	[S/Zn]	[Si/Zn]
$-0.86^{+0.15}_{-0.15}$	$-1.90^{+0.22}_{-0.14}$	$-1.62^{+0.09}_{-0.09}$	$-1.28^{+0.14}_{-0.14}$	$-1.04^{+0.25}_{-0.19}$	$-0.76^{+0.16}_{-0.16}$	$-0.42^{+0.19}_{-0.19}$

^a We use the normal notation where $[X/Y] = \log(X/Y) - \log(X/Y)_{\odot}$.

$\approx 20 \text{ km s}^{-1}$ is derived from a curve of growth generated from the three observed Si II absorptions. This b -value is much larger than that for the H₂ absorption, indicating probably more than one velocity component associated with the $z = 2.3374$ metal line system. However, Jenkins (1986) has demonstrated that multicomponent line profiles can be approximated as single-component Gaussians for the purpose of deriving column densities if none of the components are heavily saturated. Therefore, we can use the single b -value curve of growth to derive column densities of the weakly saturated lines such as Fe II $\lambda 1608$ and S II $\lambda 1253$. The column density of Zn II is derived assuming it is not saturated. The depletions of Zn, Fe, S, and Si were calculated using the total measured $N(\text{H})$ and using the solar abundances from Grevesse, Noels, & Sauval (1996) as reference. The depletions thus derived for these species are listed in Table 2. We have assumed that $N(\text{Zn II})/N(\text{H})$, $N(\text{Fe II})/N(\text{H})$, $N(\text{S II})/N(\text{H})$, and $N(\text{Si II})/N(\text{H})$ reflect their corresponding gas-phase abundances because these ions are the dominant species in the DLAs (e.g., Pettini et al. 1994).

The metallicity in the $z = 2.34$ DLA, represented by Zn, is among the highest in all the high-redshift DLAs with measured Zn abundances (Pettini et al. 1994, 1997). The dust depletion, represented by the relative abundance ratio of $[\text{Fe}/\text{Zn}] = -1.04$, is also very high. Since the extent of depletion of Fe is almost equal to that of Cr in the interstellar medium of the Milky Way and other high-redshift DLAs (Jenkins 1987; Lu et al. 1996), the value of $[\text{Cr}/\text{Zn}]$ in the $z = 2.34$ DLA is expected to be around -1.0 . Compared with Zn, S is significantly underabundant, which is surprising. If Type II supernovae are the dominant contributors to heavy elements, as possibly seen in most low-metallicity DLAs (Lu et al. 1996), then we should expect an overabundance of S over Zn since S arises mainly in Type II supernovae and Zn arises mainly in Type I supernovae. The underabundance of S in the $z = 2.34$ DLA may indicate that Type I supernovae dominate the metal-enrichment process in this particular absorption system. In other words, this system should be much older than 1 Gyr, which is the lifetime scale of a typical progenitor of Type I supernovae, and the relative mix of stars in this absorber may include a higher fraction of low-mass stars, thus resulting in a higher ratio of the rates of Type I to Type II supernovae.

The detection of C I is used to derive the excitation temperature of its fine structure in order to put an upper limit on

the cosmic microwave background radiation (CMBR) temperature at $z = 2.34$. As shown in Figure 2, C I and C I* absorption lines are clearly detected in the Q1232+0815 spectrum, which is also confirmed by recent the VLT observations (Petitjean et al. 2000). The $J = 0$ absorption line is present in the C I UV multiplet 2 at 1656.93 \AA . C I $J = 1$ absorption is present at 1656.27 and 1657.91 \AA . No absorption feature for $J = 2$ at 1658.121 \AA is detected. Furthermore, the C I $J = 0$ absorption line at $\lambda = 1656.928 \text{ \AA}$ is blended with one of the C I $J = 1$ lines at $\lambda = 1657.379 \text{ \AA}$ and also one of the C I $J = 2$ lines at $\lambda = 1657.008 \text{ \AA}$. The column density in the $J = 0$ level of C I is derived by assuming that the absorption at $\lambda = 5528.37 \text{ \AA}$ is only from the $J = 0$, $\lambda = 1656.928 \text{ \AA}$ since the strengths of other blended lines such as $J = 1$, $\lambda = 1657.379 \text{ \AA}$ and $J = 2$, $\lambda = 1657.008 \text{ \AA}$ are much weaker than that of the $J = 0$ line. The other two $J = 1$ lines of C I multiplet 2, $\lambda 1656.267$ and $\lambda 1657.907$ are detected at about the $2\text{--}3 \sigma$ level, and in the weighted mean they are present at the 4σ level. The weighted mean is used to derive the population ratio of the $J = 1$ and $J = 0$ levels, as shown in Table 3. Since the absorption lines from C I and C I* are very weak, a linear approximation was made in the derivation of their column densities. The derived excitation temperature of the C I based on the population ratios $N(J = 1)/N(J = 0)$ is $T_{\text{ex}} = 15.7 \pm 3.5 \text{ K}$. This temperature is an upper limit for the CMBR temperature at $z = 2.34$ because the C I fine-structure level can be excited not only by the CMBR field but also by other excitation sources such as collisions and UV pumping. This upper limit on the CMBR temperature at $z = 2.34$ is consistent with the predicted value at this redshift, $T_{\text{CMBR}} = 9.100 \text{ K}$.

4. DISCUSSION

Since our spectral resolution is not sufficient to resolve the absorption-line profiles, the uncertainty in the total derived H₂ column density is relatively large. Our simulations of H₂ spectra show that they are very sensitive to the adopted Doppler b -value. For example, if a big b -value such as $b = 10 \text{ km s}^{-1}$ as seen in one of diffuse clouds in the SMC is adopted (Shull et al. 2000), then the best-fitted total H₂ column density $N(\text{H}_2) \approx 3.0 \times 10^{17} \text{ cm}^{-2}$. The uncertainty in total derived H₂ column density is likely to be about 2 orders of magnitude. Indeed, spectroscopy at higher spectral resolution is needed to address this uncertainty as confirmed by recent VLT observations by P. Petitjean's group (Petitjean et al. 2000).

Although the uncertainty for the total H₂ column density is large, the range of the fractional H₂ abundance, $f \sim (0.07\text{--}7) \times 10^{-4}$, is still much higher than the rest of the DLAs searched before (Ge & Bechtold 1999). The relatively high molecule abundance may be related to the relatively high dust content found in this DLA. To study systematically the relationship between the H₂ abundance and the dust content in the high-redshift DLAs, we plot all the available measurements of the H₂ abundance and dust depletion in Figure 3. The measurements include upper limits on H₂ abundance in four DLAs from the literature (Black, Chaffee, & Foltz 1987; Foltz et al.

TABLE 3
EXCITATION TEMPERATURE OF C I AT
 $z = 2.3384$

C I Multiplet 2	Density
$N(\times 10^{13} \text{ cm}^{-2})^{\text{a}}$	
$J = 0, \lambda = 1656.928 \text{ \AA} \dots\dots$	2.4 ± 0.3
$J = 1, \lambda = 1656.267 \text{ \AA} \dots\dots$	1.5 ± 0.6
$J = 1, \lambda = 1657.907 \text{ \AA} \dots\dots$	1.8 ± 0.8
$\langle J = 1 \rangle_{\text{weighted}} \dots\dots\dots$	1.6 ± 0.5
$N(J = 1)/N(J = 0) \dots\dots\dots$	0.67 ± 0.22
$T_{\text{ex}} (\text{K}) \dots\dots\dots$	15.7 ± 3.5

^a We assume that the absorption lines are not saturated.

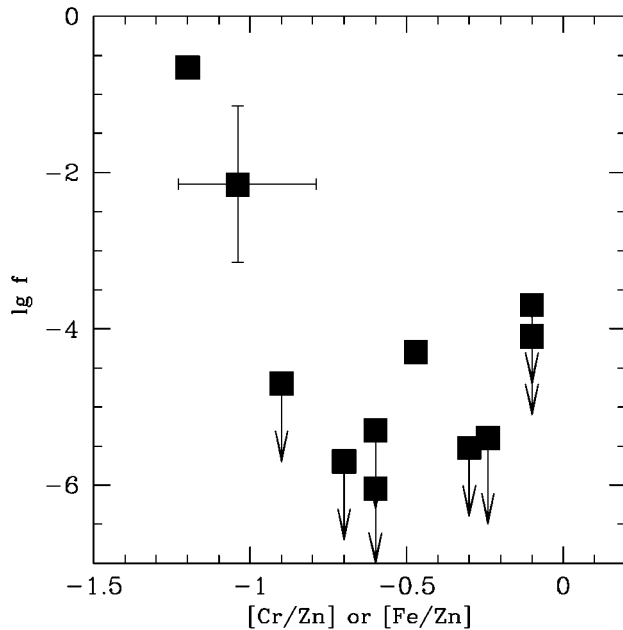


FIG. 3.—Correlation between the fractional H_2 abundance f and the relative heavy-element depletion, $[Cr/Zn]$ or $[Fe/Zn]$ (see Table 2 for the notation of $[X/Y]$), in 11 high-redshift DLAs from the compilation by Ge & Bechtold (1999). The redshift range is $z_{\text{abs}} = 0.7\text{--}3.4$. The averaged redshift is $z_{\text{abs}} = 2.1$. The errors associated with the $z = 2.34$ DLA measurements are marked.

1988; Lanzetta, Wolfe, & Turnshek 1989; Levshakov et al. 1992), four DLAs from our survey, and three DLAs from the *HST* archival data (see Ge & Bechtold 1999 for a review). The detailed analysis of these seven DLAs and the 10 other DLAs searched by us will be published in a separate paper (J. Ge et al. 2000, in preparation). Figure 3 shows a correlation between the fractional H_2 abundance and the metal depletion that is similar to what has been found in the local diffuse clouds (Jenkins 1987). In the diffuse clouds in the Milky Way, the

depletions of Fe and Cr relative to Zn are caused by the selective condensation of heavy elements on interstellar dust grains (e.g., Jenkins 1987). Therefore, our result suggests that the dust grains existing in these high-redshift DLAs may also play an important role in H_2 formation. This new result is also consistent with previous conclusions that dust in the DLAs causes the observed reddening of the quasar spectra and the observed relative depletion of heavy elements (Pei, Fall, & Bechtold 1991; Pettini et al. 1994, 1997; Kulkarni, Fall, & Truran 1997). However, since the sample is relatively small, uncertainty is still large. A larger sample should be acquired in the future so as to investigate further the relationship between the molecule content and dust depletion.

The detections of C I and H_2 absorption in this system and the $z = 1.97$ DLA (Ge, Bechtold, & Black 1997a; Ge & Bechtold 1997) indicate that H_2 and C I are coexisting in these systems, similar to the results found by the *Copernicus* observations (Federman et al. 1980). These results are consistent with our theoretical simulation results with the CLOUDY program (Ge et al. 1997a, 1997b; Ferland 1993). The CLOUDY results show that H_2 and C I trace the same region of the clouds and that their column densities are strongly correlated and are sensitive to the UV radiation field. Therefore, the nondetection of H_2 absorption in most DLAs is consistent with the nondetection of C I absorption in them (L. Lu 1997, private communication). This result suggests that the UV radiation intensity in most DLAs could be higher than that in the DLAs at $z = 1.97$ and $z = 2.34$. However, the nondetection of H_2 and C I could also be caused by other effects such as low dust content and low metallicity.

We thank John Black for providing us with his H_2 absorption-line synthesis code and for his helpful discussions. We thank an anonymous referee for the comments he or she made that improved this Letter. We also thank the staff of the MMT Observatory for their help. This research was supported by NSF grants AST 96-17060 and AST 90-58510 and NASA STScI grant AR-05785.

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