MOLECULAR HYDROGEN ABSORPTION IN THE $z = 1.97$ DAMPED Ly$\alpha$ ABSORPTION SYSTEM TOWARD QUASI-STEellar OBJECT Q0013$-$004

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ABSTRACT

We present a new ultraviolet spectrum of the quasi-stellar object Q0013$-$004 with 0.9 Å resolution obtained with the Multiple Mirror Telescope Blue Spectrograph. The $v = 0$–0, 1–0, 2–0, and 3–0 Lyman bands of H$_2$ associated with the $z = 1.9731$ damped Ly$\alpha$ absorption-line system have been detected. The H$_2$ column density is $N$(H$_2$) $= 6.9(\pm 1.6) \times 10^{19}$ cm$^{-2}$, and the Doppler parameter $b = 15 \pm 2$ km s$^{-1}$. The populations of different rotational levels are measured and used to derive the excitation temperatures. The estimated kinetic temperature $T_k \sim 70$ K, and the total particle number density $n(H) \sim 300$ cm$^{-3}$. The UV photoabsorption rate $\beta_H \sim 6.7 \times 10^{-9}$ cm$^{-3}$ s$^{-1}$, about a factor of a few times greater than that in a typical diffuse Milky Way interstellar cloud. The total hydrogen column density is $N(H) = 6.4(\pm 0.5) \times 10^{20}$ cm$^{-2}$. The fractional H$_2$ abundance $f = 2N(H_2)/[2N(H_2) + N(H_I)] \sim 0.22 \pm 0.05$ is the highest among all observed damped Ly$\alpha$ absorbers. The high fractional H$_2$ abundance is consistent with the inferred presence of dust and strong C i absorption in this absorber.

Subject heading: ISM: molecules — quasars: absorption lines — quasars: individual (Q0013$-$004)

1. INTRODUCTION

Damped Ly$\alpha$ quasar absorption-line systems are commonly believed to trace a population of objects that may be the progenitors of modern galaxies (e.g., Wolfe 1990). The typical metallicity and dust-to-gas ratio in the damped Ly$\alpha$ systems at $z \sim 2$ is measured to be about 10% of those in the Milky Way with a large scatter (e.g., Pettini et al. 1994, 1995; Pei, Fall, & Bechtold 1991; Lu 1996). The UV Lyman and Werner bands of H$_2$ have been difficult to detect, however, so that little is known about molecular gas in damped Ly$\alpha$ galaxies (Levshakov et al. 1992; Lanzetta, Wolfe, & Turnshek 1989; Foltz, Chaffee, & Black 1988; Chaffee, Foltz, & Black 1988; Black, Chaffee, & Foltz 1987). The problem such searches face is that without high-resolution and high signal-to-noise (S/N) ratio spectra, the molecular hydrogen lines are blended with the Ly$\alpha$ forest lines. Furthermore, quasar absorption-line studies usually concentrate on bright blue quasars; thus, lines of sight with substantial reddening and large molecular fraction are probably selected against (Ostriker & Heisler 1984; Fall & Pei 1993). So far, there is only one detection of H$_2$ absorption in the $z = 2.811$ damped Ly$\alpha$ absorber toward PSK 0528$-$250, which shows moderate H$_2$ absorption with total column density $N$(H$_2$) $= 1 \times 10^{19}$ cm$^{-2}$ (Foltz et al. 1988; Lanzetta 1993). This system may not be representative, since its redshift is very close to the redshift of the quasar.

Previous observations of the $z_a = 1.9731$ damped Ly$\alpha$ absorber toward Q0013$-$004 ($z_{em} = 2.0835$) showed C i absorption, and line ratios of Cr ii, Fe ii, and Zn ii indicated significant depletion and hence a relatively high dust-to-gas ratio compared to other damped Ly$\alpha$ absorbers (Pettini et al. 1994; Ge, Bechtold, & Black 1997). Thus, it seemed to be a good system to search for H$_2$. In this Letter, we report the detection of strong H$_2$ absorption lines.

2. OBSERVATIONS

Spectra were obtained with the Multiple Mirror Telescope (MMT) on 1995 October 13 and October 24–25 with the Blue Channel Spectrograph and the Loral 3072 $\times$ 1024 CCD. The 832 line mm$^{-1}$ grating was used in second order. A 1” $\times$ 180” slit was used to give a resolution of 0.9 Å, corresponding to 2.6 pixels, measured from the comparison lamp lines. The wavelength coverage was from 3000 Å to 4100 Å. The seeing was 1.0” (FWHM). The integration was composed of 12 separate exposures of 50 minutes each. The quasi-stellar object (QSO) was stepped by a few arcseconds along the slit between each exposure to smooth out any residual irregularities in the detector response that remained after flat-fielding. An exposure of an He-Ne-Ar-Cu lamp was done before and after each exposure of the object to provide an accurate wavelength reference and a measure of the spectral resolution. Several quartz lamp exposures were taken at the beginning and end of the nights to provide a flat-field correction. We also observed standard stars before and after the QSO observations to monitor possible atmospheric absorption.

The data were reduced in the standard way using IRAF. The He-Ne-Ar-Cu spectra were extracted with the same procedure, and a first-order Spline3 function fit was used to obtain a wavelength calibration. The root mean square residuals to the wavelength fit are typically 0.05 Å. All reported wavelengths are vacuum and have been corrected to the heliocentric frame. We have rebinned pixels in the common wavelength ranges of the spectra from the two observation runs and combined them, weighted by the S/N ratio. Part of the summed spectra are shown in Figures 1a and 2. The S/N ratio is about 10 per pixel in the wavelength range of 3150–3350 Å, which covers the H$_2$ absorption bands. The S/N ratio is about 20 or higher in the wavelength range of 3500–3750 Å, which covers the damped Ly$\alpha$ absorption. The continuum was fitted in the way described by Bechtold (1994). The spectra shown were normalized by their fitted continuum.

1 Observations here were obtained with the Multiple Mirror Telescope, a joint facility of the University of Arizona and the Smithsonian Institution.
1. The neutral hydrogen column density is evident caused by shifting two spectra with one Lyman band separation (~47 Å in the observed frame).

2. The correlation amplitude is 0.66 for lower redshifts. The measured fractional H$_2$ abundance, $f = 2N$(H$_2$)/[2N(H$_2$) + N(H I)] = 0.22 ± 0.05, is about a factor of lines is the result of chance coincidence with Ly$_\alpha$ in the observed frame, e.g., Morton & Dinerstein 1976). If the regions in the spectrum around the four identified strong Ly$_\alpha$ and metal lines, as marked in Figure 1a (3216.2–3224.9 Å, 3296.1–3300.3 Å), are removed from the data before the correlation is carried out, then the peak correlation amplitude is 0.82. The measured redshift for the H$_2$ absorption corresponding to the peak position of the cross-correlation function, $z_{HI} = 1.9731$, is consistent with the redshift of the metal lines (Ge et al. 1997).

In order to estimate the statistical significance of the correlation amplitude, we have simulated Ly$_\alpha$ forest line spectra using the program described in Dobrzycki & Bechtold (1996). In order to be conservative, we made synthetic spectra that matched the total absorption-line density of all the strong lines in the Q0013–004 spectrum between 3150 and 3350 Å, even though several of the strong lines are actually metal transitions for the $z = 1.97$ system. We cross-correlated 1000 simulated spectra with the synthetic H$_2$ absorption-line spectrum. The peak values of the cross-correlation function are all smaller than 0.55. Thus, the probability of obtaining a correlation peak of 0.66 by chance is less than 10$^{-4}$.

To obtain column densities from the measured values of equivalent width (Table 1), a curve of growth was constructed for $J = 2$, 3, 4, 5 rotational levels, showing the theoretical curves for the 0–0 Lyman band with different Doppler $b$ values, $b = 10$, 13, 15, 17, 20 km s$^{-1}$. Absorption lines for $J = 4, 5$ are on the linear section. Absorption lines from $J = 2, 3$ are on the flat section. The observed values for $J = 2, 3, 4$ and 5 are consistent with $b = 15 ± 2$ km s$^{-1}$. Table 2 shows the derived column densities for $J = 2, 3, 4$ assuming the $b = 15 ± 2$ km s$^{-1}$, and upper limits for $J = 5, 6, 7$ assuming that they are on the linear portion of the curve of growth. Column densities from $J = 0, 1$ are derived by the continuum-reconstruction procedure described by Savage et al. (1977), i.e., a reconstruction of the QSO spectrum was generated by dividing the observed spectrum by the synthetic H$_2$ spectrum of $R(0)$, $R(1)$, and $P(1)$ lines. The final values of $N(J = 0)$ and $N(J = 1)$ were determined from the best-fit reconstructions of (2, 0), (1, 0), and (0, 0) Lyman bands (Table 2). The uncertainties in the final column densities were estimated by the same procedure. Together, the total H$_2$ column density is $N$(H$_2$) = 6.9(±1.6) × 10$^{19}$ cm$^{-2}$.

Table 2 also includes the derived excitation temperatures for the rotational levels. The measured $T_{ex} = 70 ± 13$ K is in the range of typical values of the Milky Way diffuse clouds (Savage et al. 1977) and is also similar to the $T_{ex} = 2.811$ damped Ly$_\alpha$ absorber of PKS 0528–250 (Songaila & Cowie 1995). The $T_{ex} = 82.17 ± 16$ K is also in the range of the average value for the Milky Way clouds. The excitation temperatures for higher $J, T_{ex}$ of 200–500 K, are similar to that of Milky Way clouds (Spitzer, Cochran, & Hirshfeld 1974).

Figure 2 shows the observed damped Ly$_\alpha$ profile and fits to the line profile. The neutral hydrogen column density is $N$(H I) = 5.0(±0.5) × 10$^{19}$ cm$^{-2}$, the Doppler parameter is $b_{HI} = 50$ km s$^{-1}$, and $z_{HI} = 1.9731$. The neutral hydrogen absorption redshift is consistent with the metal-line and H$_2$ redshifts. The measured fractional H$_2$ abundance, $f = 2N$(H$_2$)/[2N(H$_2$) + N(H I)] = 0.22 ± 0.05, is about a factor...
of 60 times higher than that of the z = 2.811 damped Lyα system toward PKS 0528–250, and the limits for other damped systems previously searched for H2 absorption (Black et al. 1987; Chaffee et al. 1988; Foltz et al. 1988; Lanzetta et al. 1989; Levshakov et al. 1992; Songaila & Cowie 1996).  

4. DISCUSSION  

The molecular fraction $f = 0.22 \pm 0.05$ for the z = 1.97 absorber is similar to that seen in $E(B - V) > 0.1$ clouds in the Milky Way (Savage et al. 1977). Indeed, the upper limit of the relative depletion of Cr to Zn, $[\text{Cr}/\text{Zn}] \leq -1.0$ (Pettini et al. 1994) suggests that the dust-to-gas ratio in this absorber is much higher than the average value of 10% of the Milky Way’s ratio for damped systems at z = 2 (Pettini et al. 1994). The previous observation of Fe II λ 1608.45 Å provides a direct comparison of the relative depletion of Fe to Zn, $[\text{Fe}/\text{Zn}] = -1.2$ (Ge et al. 1997) to those of the Milky Way’s diffuse clouds. Table 3 shows a comparison between the z = 1.9731 absorber and the diffuse clouds toward ζ Oph and ξ Per (Spitzer et al. 1974; Savage et al. 1977; Jura 1975; Savage, Cardelli, & Sofia 1992; Cardelli et al. 1991). The relative depletion of [Fe/Zn] implies that the dust-to-gas ratio in the z = 1.9731 absorber is about 50% of the Milky Way’s value. The relative normal dust-to-gas ratio is consistent with the high H2 fraction because H$_2$ is very efficiently formed on dust grain surfaces (Savage et al. 1977).

As discussed by previous reviews (e.g., Spitzer & Jenkins 1975; Shull & Beckwith 1982), the relative populations of J = 0 and 1 are established dominantly by thermal particle collisions, especially for saturated lines, so that the excitation temperature $T_\text{ex}$ is approximately equal to the kinetic temperature $T_\text{kin}$ of the clouds. The measured $T_{\text{ex}} = 70 \pm 13$ K in the z = 1.9731 absorber implies that the kinetic temperature is similar to that of the Milky Way diffuse clouds, $T_{\text{ex}} = (77 \pm 17)$ K (Savage et al. 1977). The higher rotational levels are populated primarily by collisions, formation pumping and UV pumping, and radiative cascade after photoabsorption to the Lyman and Werner bands (e.g., Spitzer & Zweibel 1974; Jura 1974, 1975). For example, the J = 4 level is populated by direct formation pumping and by UV pumping from J = 0 (e.g., Black & Dalgarno 1976). For densities less than $10^4$ cm$^{-3}$, the J = 4 level is depopulated mainly by spontaneous emission (Dalgarno & Wright 1972; Elitzur & Watson 1978). Therefore, in a steady state for $J = 4$,  

$$p_{\alpha \beta}(0)n(H_2, J = 0) + 0.19n(H)n = A_{\alpha \beta}n(H_2, J = 4),$$

(1)
where \( p_{b0} = 0.26 \) is the UV pumping efficiency into the \( J = 4 \) level from the \( J = 0 \) level (Jura 1975), \( A_{12} = 2.8 \times 10^{-8} \) s\(^{-1}\) is the spontaneous transition probability (Dalgarno & Wright 1972), \( R \) is the \( \text{H}_2 \) formation rate, \( n = n(H) + 2n(H_2) \), and \( \beta(J) \) denotes the rate of absorption in the Lyman and Werner bands from the \( J/\)th rotational level, including any attenuation (see Jura 1975 for details). The equilibrium between the \( \text{H}_2 \) formation on dust grains and \( \text{H}_2 \) destruction by absorption of Lyman- and Werner-band radiation (e.g., Jura 1975) can be written as

\[
\ln(n_{\text{H}_2}) = Rn(H)n \approx 0.11 \sum_{J=0}^{\infty} \beta(J)n(H_2, J),
\]

where \( n \) is the \( \text{H}_2 \) dissociation rate (Jura 1975). If the self-shielding in \( J = 0, 1 \) levels is about the same, so that \( \beta(0) \approx \beta(1) \), then

\[
n(H_2, J = 4) = A_{12} = 1.52Rn(H)n.
\]

Thus, \( Rn = 8.1(1.38 \times 10^{-15} \) s\(^{-1}\) for the Q0013–004 cloud, which is about the same magnitude as that for \( \xi \) Per and \( \zeta \) Oph clouds (Jura 1975).

We can use the analytic calculation for \( n(H_2)/n(H) \) within an \( \text{H}_2 \) cloud by Jura (1974) to estimate the \( \text{H}_2 \) dissociation rate \( I \approx 7.4 \times 10^{-10} \) s\(^{-1}\). The photoabsorption rate in the Lyman and Werner bands outside of the cloud is \( \beta_0 \approx \sigma / (1 + 0.1) \approx 6.7 \times 10^{-8} \) s\(^{-1}\), which is similar to that of the \( \xi \) Per cloud (Jura 1975) and about a factor of a few higher than that of \( \zeta \) Oph cloud (Federman et al. 1995). Further, the photoabsorption rate, \( \beta_0 \), depends linearly on the local radiation field at 930–1150 Å (Jura 1974); therefore, the \( \beta_0 \) value for the \( z = 1.9731 \) absorber corresponds to an estimated local radiation field at 1000 Å of \( L_{1000} \lambda \approx 3 \times 10^{-18} \) erg cm\(^{-2}\) s\(^{-1}\) Hz\(^{-1}\) sr\(^{-1}\). Thus, \( J_{12} \lambda \) is about 3 orders of magnitude higher than the radiation field at the Lyman limit, \( J_{12} \lambda \) expected in the ambient intergalactic medium at this redshift (e.g., Wu, Wolfe, & Turnshek 1991; Bechtold 1994). The radiation field at 1000 Å is therefore probably dominated by the UV emission by hot stars in this galaxy.

As mentioned above, the \( z = 1.9731 \) absorber has a similar dust-to-gas ratio to that of the Milky Way diffuse clouds. If we assume the \( \text{H}_2 \) formation rate on grains, \( R \sim 3 \times 10^{-17} \) cm\(^3\) s\(^{-1}\), the typical rate for the Milky Way’s clouds (Jura 1975), then the inferred value of the number density is \( n \sim 300 \) cm\(^{-3}\), about the same as that of the \( \zeta \) Oph and \( \xi \) Per clouds.

The derived values of the UV radiation field, density, and temperature in the \( z = 1.97 \) absorber are estimates based on the simple analysis of Jura (1975), which ignores the depth dependence of the attenuation by dust and self-shielding of absorption lines. However, the results from this simple analysis are qualitatively consistent with that from more detailed modeling (e.g., van Dishoeck & Black 1986).

We note that there is some uncertainty in the derived \( b \) value. While \( b = 15 \) km s\(^{-1}\) provides the best fit to the observed values, smaller Doppler parameters, for example, \( b = 2 \) km s\(^{-1}\), also give an acceptable solution. In this case, the implied column densities in \( J = 2, 3, \) and 4 levels are so high that they would suggest that conditions more like a photon-dominated region are implied (e.g., Draine & Bertoldi 1996; Black & van Dishoeck 1987; Abgrall et al. 1992; Le Bourlet et al. 1993; Sternberg & Dalgarno 1989). The populations in \( J = 2, 3, \) and 4 levels would be fitted by a single excitation temperature of 350 K. This would leave excess population in \( J = 0 \) and 1 levels, suggesting a cold component at \( T_{\text{ex}} \approx 63 \) K.

The density of the absorber cloud would have to be lower than about 5000 cm\(^{-3}\) in order for the \( J = 5 \) limit to be consistent with the populations in \( J = 2, 3, \) and 4.

Finally, if the larger value \( b = 15 \) km s\(^{-1}\) is correct, then this absorber has a \( b \) value that is much larger than that for typical Milky Way diffuse clouds (e.g., Spitzer et al. 1974). This would indicate that there is likely more than one velocity component. Spectra of higher resolution would permit a better constrained analysis of the excitation and molecular abundance and provide a better understanding of physical conditions in this high-redshift galaxy.

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