MISSING MOLECULAR HYDROGEN AND THE PHYSICAL CONDITIONS OF GRB HOST GALAXIES

JASON TUMLINSON, JASON X. PROCHASKA, HSIAO-WEN CHEN, MIROSLAVA DESSAUGES-ZAVADSKY, AND JOSHUA S. BLOOM

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ABSTRACT

We examine the abundance of molecular hydrogen (H₂) in the spectra of gamma ray burst afterglows (GRBs). In nearby galaxies, H₂ traces the cold neutral medium (CNM) and dense molecular star-forming interstellar gas. Although H₂ is detected in at least half of all sight lines toward hot stars in the Magellanic Clouds and in ~25% of damped Lyα systems toward quasars, it is not detected in any of the five GRB environments with a similar range of neutral hydrogen column density and metallicity. We detect no vibrationally excited H₂ that would imply that the GRB itself has photodissociated its parent molecular cloud, so such models are ruled out unless the parent cloud was ≤4 pc in radius and was fully dissociated prior to the spectroscopic observations, or the star escaped its parent cloud during its main-sequence lifetime. The low molecular fractions for the GRBs are mysterious in light of their large column densities of neutral H and expectations based on local analogs, i.e., 30 Doradus in the LMC. This surprising lack of H₂ in GRB damped Lyα absorbers indicates that the destruction processes that suppress molecule formation in the LMC and SMC are more effective in the GRB hosts, most probably due to a combination of low metallicity and an FUV radiation field 10–100 times the Galactic mean field. These inferred conditions place strong constraints on the star-forming regions in these early galaxies.

Subject headings: gamma rays: bursts — ISM: molecules

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1. INTRODUCTION

In the Milky Way, stars are born within molecular clouds where cooling by atoms and molecules is sufficient to achieve very high densities. Stars are also observed to form within molecular complexes in the Magellanic clouds, and local starbursts exhibit large molecular gas masses. The qualitative connection between molecular gas and star formation is therefore well known in the local universe, although resolving the key physical processes is an area of active research. Theoretical treatments of star formation in the early universe predict that H₂ is the main coolant of gas with primordial composition (Abel et al. 1997), but the role of metals and dust in forming the first metal-enriched stars is poorly understood (Schneider et al. 2002; Santoro & Shull 2006). Current instruments cannot directly measure the molecular mass in galaxies at high redshift, so the metallicity and/or time dependence of star formation in the early universe has not yet been mapped out.

While we await new millimeter and radio telescopes that can detect molecular gas at high redshift, absorption-line spectroscopy of quasars and gamma-ray burst (GRB) afterglows offer a means of studying H₂ in low-metallicity environments, at least in the diffuse interstellar medium (ISM). Molecular hydrogen has been surveyed extensively in the Milky Way (Savage et al. 1977, hereafter S77; Gillimon et al. 2006) and Magellanic Clouds (Tumlinson et al. 2002, hereafter T02) by Copernicus and the Far Ultraviolet Spectroscopic Explorer (FUSE), and in the ISM of high-z galaxies that intercept the sight lines of distant quasars, i.e., damped Lyα systems (QSO-DLAs; Wolfe et al. 2005; Petitjean et al. 2000; Ledoux et al. 2003). Because the QSO-DLA population is usually selected according to gas cross-section, quasar sight lines preferentially penetrate the outer regions of a galaxy’s ISM, and will very rarely intersect molecular clouds with sizes typical of the local universe (Zwaan & Prochaska 2006). DLAs typically have low metallicity (≤0.1 solar), and may have robust ongoing star formation, both of which act to suppress the formation of H₂, and may explain the large fraction of DLAs for which H₂ is not detected (Cui et al. 2005; Hirashita & Ferrara 2005; Petitjean et al. 2006; Ledoux et al. 2003; Tumlinson et al. 2002). Also, DLAs may preferentially sample the warm neutral medium of intervening galaxies, with gas too warm for H₂ to form efficiently on the surfaces of dust grains (Petitjean et al. 2000). While a causal connection between metallicity and the formation of H₂ in QSO-DLAs is suggested by a marked increase in H₂ detection rates above ~20% solar (Petitjean et al. 2006), the relative importance of UV radiation and geometric cross-section in determining the abundance of H₂ in QSO-DLAs is not yet known.

Because their progenitors are massive stars (Woosley 1993), long-duration GRBs occur within the star-forming regions of galaxies (Bloom et al. 2002; Fruchter et al. 2006). At UV and optical wavelengths, the unextinguished broadband spectra of GRB afterglows appear consistent with power laws ($f_{\nu} \sim \nu^{-1.2}$, e.g., Kann et al. 2006), as expected from a synchrotron shock origin (Sari et al. 1998). Early-time spectroscopy of these afterglows allows studies of the ISM of the host galaxy and the intergalactic medium along the sight line (e.g., Savaglio & Fall 2004; Vreeswijk et al. 2004; Chen et al. 2005). In this paper, we survey the H₂ content of the diffuse gas seen in absorption toward GRB afterglows, and compare these against previous measurements of the Milky Way, Magellanic Clouds, and DLA populations. Related papers
The H$_2$ molecule exhibits bands of absorption in two electronic transitions (Lyman and Werner; hereafter LW) at rest wavelengths $\lambda = 900$–1120 Å, which are broken into hundreds of individual lines by quantized vibrational and rotational excitation modes (see Shull & Beckwith 1982 for a review of the molecular physics). Approximately 11% of photoabsorptions in these bands are followed by decay to the vibrational continuum and dissociation of the molecule. Because it forms on the surfaces of dust grains, the formation rate of H$_2$ is directly proportional to the local dust-to-gas ratio. The balance of these formation and destruction processes determines the molecular fraction of H$_2$, $f_{H_2} = 2N_{H_2}/(N_{H_1} + 2N_{H_1})$. Thus, a measurement of $f_{H_2}$ and relative populations in the various rotational levels of the ground vibrational state can serve as sensitive diagnostics of local physical conditions such as density, temperature, and ambient FUV radiation field (T02; Browning et al. 2003; Srianand et al. 2005; Noterdaeme et al. 2007). For galaxies at $z > 2$, the LW bands are redshifted into the range of ground-based optical telescopes, and can be found in the spectra of a bright background source. High spectral resolution ($R \approx 30,000$) is desirable because (1) the H$_2$ lines have intrinsic widths of one to a few km s$^{-1}$, and (2) the transitions are located within the LW forest, where line blending can be severe. Table 1 summarizes the five GRBs that have been observed at $z > 2$ with adequate spectral resolution and coverage of the LW bands.

All of these GRB sight lines exhibited damped Ly$\alpha$ profiles at the redshift of the host galaxy (termed a GRB-DLA). The H$\alpha$ column density $N_{H_1}$ was derived from Voigt profile fits to the Ly$\alpha$ transition; all exceeded the nominal DLA cutoff of $N_{H_1} \geq 2 \times 10^{20}$ cm$^{-2}$. The gas-metallicities [M/H] were measured with low-ion transitions of Si, S, or Zn, assuming no corrections for differential depletion or ionization (Prochaska et al. 2007a). We also report estimates of the depletion of [M/Fe] normalized to the solar ratio and not corrected for any possible nucleosynthetic variations. The Ti/Fe ratios in GRB-DLA indicate that the gas is depleted (Prochaska et al. 2007a) and that the intrinsic contribution to [M/Fe] is likely only $0.3$ dex, if we assume standard values observed in metal-poor stars (e.g., McWilliam 1997).

With the exception of GRB 060206, we either acquired the spectra of the sight lines in Table 1 or retrieved the spectra from the ESO-VLT archive (see Vreeswijk et al. 2004; Chen et al. 2005; Prochaska et al. 2007a; Fynbo et al. 2006 for previous analyses). We searched for the strongest H$_2$ transitions at the systemic redshift (determined from low-ion transitions redward of the Ly$\alpha$ forest) and selected regions of otherwise unoccupied continuum to avoid coincident Ly$\alpha$ forest transitions. In all cases we had good coverage of strong $R(0)$ and $R(1)$ transitions (i.e., transitions out of the $J = 0$ or $J = 1$ rotational levels of the ground vibrational state; see Fig. 1). Of the four GRB sight lines studied here, none show detectable H$_2$ to very low column density limits (4$\sigma$).

Fynbo et al. (2006) reported a tentative detection of H$_2$ from the $W(1-0)$ transition toward GRB 060206. An examination of their Figure 1 reveals that the line identified as $Q(1)$ ($f_0 = 0.0365$) has an unexpectedly high equivalent width compared to the combined strength of the $R(0)$ and $R(1)$ lines ($f_0 = 0.0699$ and 0.0340, respectively). Even in the unlikely case that $R(0)$ makes no contribution to the bluer profile, the $R(1)/Q(1)$ ratio should be 0.9, but appears to be substantially lower. This claimed detection based on only three possible lines from two rotational levels in the strongest Werner band, and unconfirmed by other bands, would not usually count as a detection according to the standards employed by, e.g., Tumlinson et al. (2002) in their H$_2$ survey of the LMC and SMC. In that study, three unblended lines from at least two bands were needed for a detection. Therefore, we must allow that the absorption lines fitted by Fynbo et al. (2006) are instead coincident Ly$\alpha$ forest lines. Here, we adopt the more stringent criteria for a detection, and treat their measurement as an upper limit to $f_{H_2}$. We perform some statistical tests below counting 060206 as both a detection and an upper limit.

3. THE INCIDENCE OF H$_2$ IN GRB-DLAs

The absence of H$_2$ in the diffuse gas of GRB-DLAs is somewhat surprising, given the large $N_{H_1}$ associated with these absorbers. Every such sight line in the Milky Way disk studied with Copernicus (S77) shows H$_2$. Tumlinson et al. (2002) found molecular hydrogen along 92% of SMC sight lines and 52% of LMC sight lines to similar detection limits, over a similar range of $N_{H_1}$. On the basis of the similar range in $N_{H_1}$ and [M/H], the QSO-DLAs provide perhaps the best comparison sample for the GRB-DLAs. Ledoux et al. (2003) found H$_2$ in 8 of 33 QSO-DLA systems with $z > 2$ (6 detections in the subset of 24 with $N_{H_1} \geq 2 \times 10^{20}$ cm$^{-2}$).

Figure 2 compares the cumulative detection rate for the MW, LMC, SMC, QSO-DLAs, and GRB-DLAs plotted with respect to 

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TABLE 1

| GRB        | $2_{GRB}$ | $\log N_{H_1}$ | [M/H]$^a$ | [M/Fe]$^b$ | Strong Mg$^c$ | Excited Fe$^d$ | $\log N_{H_2}^e$ | $\log N_{H_1}^d$ | References |
|------------|-----------|----------------|-----------|-----------|---------------|----------------|------------------|------------------|------------|
| 030323..... | 3.3720    | 21.90          | >-0.87    | 1.53      | Y             | N              | <15.1           | <13.9           | 1           |
| 050730..... | 3.9686    | 22.15          | -2.26     | 0.25      | ?             | Y              | <15.0           | <13.6           | 2, 3        |
| 050820..... | 2.6147    | 21.00          | -0.63     | 0.97      | N             | N              | <14.2           | <12.9           | 3           |
| 050922C.... | 2.1990    | 21.60          | -2.03     | 0.75      | W             | Y              | <14.8           | <13.5           | 4           |
| 060206..... | 4.0480    | 20.85          | -0.85     | ...       | ?             | ?              | <17.0           | ...             | 5           |

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$^a$ Metallicity derived from Si, S, or Zn abundance (see Prochaska et al. 2007a).

$^b$ See Prochaska et al. (2006).

$^c$ With the exception of 060206, the values represent 4$\sigma$ statistical upper limits on the column density of the individual lines displayed in Figure 1, assuming a linear curve of growth.

$^d$ Upper limit (4$\sigma$) based on nondetection of either L0-3P(1) at 1276.82 Å or L0-3R(2) at 1276.33 Å (see DH02). Molecular transition data from Abgrall et al. (1993).

$^e$ References.—(1) Vreeswijk et al. 2004; (2) Chen et al. 2005; (3) Prochaska et al. 2007a; (4) Piranomonte et al. 2007; (5) Fynbo et al. 2006.
to the “corrected” H column, $N_{\text{corr}}^{\text{HI}} = N_{\text{HI}} + [\text{M/H}]$, as derived from Table 1. This corrected H column is designed to place the various environments on a common metal-content scale by normalizing their gas abundances by their gas-to-dust ratios, probed by [M/H]. This adjustment attempts to remove the dependence of the H$_2$ fraction on metallicity, the most easily parameterized and therefore removed influence on $f_{\text{H}_2}$. This simple comparison allows us to assess whether physical influences beyond metallicity are needed to explain the relative incidence of H$_2$. We assume $Z_{\text{LMC}} = 0.4$, $Z_{\text{SMC}} = 0.2$, and ignore depletion. The GRBs cover roughly the same range of $N_{\text{corr}}^{\text{HI}}$, but there are no H$_2$ detections even to very low limits (discounting GRB 060206). Over the $N_{\text{corr}}^{\text{HI}}$ range, the detection rate is 52% in the LMC and 92% in the SMC. The 0%–20% detection rate in the GRBs is low, even at the same corrected $N_{\text{HI}}$, when compared with the Magellanic clouds. The QSO-DLAs resemble the GRB-DLAs in overall detection rate if the GRB 060206 is real, but achieve their maximum fraction at a lower $N_{\text{corr}}^{\text{HI}}$ than the MCs. Because this simple comparison accounts for varying metallicity, low metal content alone is not sufficient to explain the reduced H$_2$ abundance in the GRB-DLAs, and we must seek another cause (§4).

If the GRBs arise in dense star-forming regions, perhaps their best local analog of the GRB-DLAs is the 30 Doradus region of the LMC, where hundreds of massive stars have been formed...
within the last 10–20 Myr. Yet in three sight lines toward the edge and center of the region, strong H$_2$ absorption with $N_{H_2} \sim 10^{18}$–$10^{20}$ cm$^{-2}$ is seen in all cases with $f_{H_2} \sim 0.1$ (Blum & de Boer 2001; Danforth et al. 2002). Thus, proximity to a massive star-forming region does not itself indicate that no diffuse H$_2$ will be present, provided the density and metallicity are suitable. This comparison only emphasizes the central mystery of the GRB-DLAs: why do they have such high $N_{H_2}$ and such low $N_{H_2}$? We take up this question in the next section.

4. WHY IS H$_2$ ABSENT?

4.1. Chance of Statistical Fluctuation?

Might the 80%–100% nondetection rate of H$_2$ in GRB-DLAs result from random chance, even if the underlying distribution of H$_2$ is identical to the other populations? Since the detection limits on $f_{H_2}$ are very similar in the GRB-DLAs and the Magellanic Clouds, we can compare the uncorrected hit and miss statistics to ask how often we should detect H$_2$ in the GRBs, given SMC and LMC detection rates. In a sample of 5 with SMC conditions (T02), we should get 1 detection 4.6% of the time and none 1.0% of the time. For LMC conditions, we expect 1 detection 19.3% of the time and none 7.4% of the time. For the QSO-DLAs (Ledoux et al. 2003), we find 1 detection 36% of the time and none 30% of the time. These differences suggest that the actual detection rate in the GRBs is significantly different from the MCs, and possibly rarer than in the QSO-DLAs, although a larger sample is required to rule out the null hypothesis with a 99% confidence level. The available data indicate that diffuse H$_2$ is intrinsically less abundant in GRB-DLAs than in environments with similar total gas content and metallicity. This result is unexpected, given that GRBs are associated with massive stars, and that nearby massive stars form in molecular complexes with abundant H$_2$. We now examine the possible physical causes of the absence of H$_2$.

4.2. Absence of Dust?

One possibility is that H$_2$ is absent because dust is missing. H$_2$ formation is catalyzed on the surface of dust grains (Hollenbach & Salpeter 1971), so a dusty (e.g., primordial) cloud will form H$_2$ only very slowly in the gas phase. Yet the observed 0.4–1.0 dex depletions of Fe relative to S, Si, and Zn in the GRB-DLAs suggest that dust is present at normal levels given the metallicity (Prochaska et al. 2007a). Even if the dust content relative to the metallicity is normal, the dust content relative to the gas content depends on the metallicity itself. The dust-catalyzed formation rate of H$_2$ is specified as $Rn_{H_2}$, where $R$ is the volumetric formation rate per H atom, empirically estimated at $1-3 \times 10^{-17}$ cm$^3$ s$^{-1}$ in the solar neighborhood (Jura 1975), $n$ is the total particle density (cm$^{-3}$), and $n_{H_2}$ is the number density of neutral H alone. Although the scaling of $R$ with metallicity is expected to follow the overall gas-to-dust ratio, and therefore the metallicity, this scaling has not been tested below the metallicity of the Magellanic Clouds (T02). Thus, metallicity may partially account for the reduced detection rate of H$_2$ in GRB-DLAs, but the effect is present even when the metallicity effect has been removed by $N_{H_2}/N_{H_1}$. This issue is taken up again in § 4.4.

4.3. Destruction by the GRB?

Another possibility is that molecular gas has been destroyed by the GRB itself. Draine & Hao (2002, hereafter DH02) calculated the time evolution of molecular gas and dust surrounding a typical GRB afterglow, assuming that the burst occurs in a dense molecular cloud $\sim$5 pc in radius and with density $n_{H_2} = 10^3$–$10^5$ cm$^{-3}$. Their key finding is that even if the cloud starts as fully molecular at the time of the burst, H$_2$ molecules and dust will be destroyed efficiently by the advancing soft X-ray and UV radiation. In this case, one may observe a spectrum of vibrationally excited H$_2$ lines in the emergent spectrum if the parent cloud is not completely destroyed. A model spectrum of the parent cloud appears in their Figure 9, where strong absorption from H$_2$ with $N \sim 10^{21}$ cm$^{-3}$ and numerous lines of vibrationally excited H$_2$ are predicted.

Neither of these key signatures is seen in any of the GRB-DLA sight lines, to very low detection limits. The strongest predicted H$_2$ features (vibrationally excited Lyman 0 and 1–2 bands; see Table 1 of DH02), are undetected in our GRB-DLA spectra to limits of 10–60 mA. With oscillator strengths $f = 0.03$–0.05, these lines have $N \lesssim (1-10) \times 10^{13}$ cm$^{-2}$, more than 5 orders of magnitude smaller than the predictions for clouds undergoing destruction by a GRB. DH02 state that for a cloud size of 3 pc, the ionization/dissociation front reaches the cloud surface $\sim$20 s after the burst, after which time the molecular hydrogen has been completely destroyed and leaves no imprint in the spectrum. If the five detected GRBs occurred in dense molecular clouds like those studied by DH02, then clouds of size $\lesssim$4 pc would have been destroyed by the time the spectra of the afterglow was obtained. Bursts occurring within larger clouds can have their radiation fronts “stall,” leaving a strong imprint of vibrationally excited H$_2$. Thus, the absence of such excitation in our spectra indicates that either the GRBs did not form in and then dissociate their parent clouds, or those clouds were smaller than $\sim$4 pc in size, and so were destroyed before the afterglow was observed.

If GRB host star-forming regions resemble local star-forming clouds, it might be unlikely that GRBs ever occur within the parent cloud of the progenitor star. Indeed, in the Milky Way, most OB stars are not deeply embedded in their parent molecular clouds, but rather within ionized regions at the boundary of a giant molecular cloud, or in the general ISM hundreds of parsecs from a molecular cloud. Molecular clouds can be driven away from the hot stars formed within them by the “rocket effect,” in which gas is ionized from the edge of a molecular cloud, and the cloud moves away from the star(s) in reaction (Spitzer 1978). The rocket effect can drive clouds at $\sim$10–20 km s$^{-1}$ in the Milky Way disk, transporting them ~50–100 pc away in the ~3–5 Myr lifetime of a massive star (Bertoldi & McKee 1990; Krumholz et al. 2006). This effect is not known to have any explicit dependence on metallicity, so it may act in GRB host galaxies as well. Thus, we do not expect that a GRB progenitor would necessarily arise from a star that resides within a dense cloud, even though it must have been formed in one. This possibility justifies treating the GRB-DLA as though the absorbing material were not associated with the GRB progenitor itself.

We thus have no positive evidence for the association of GRBs with dense molecular clouds based on H$_2$ observations, even though they lie behind very large H I columns. The absence of H$_2$ absorption (as H$_2$ or H$_2^+$) in the afterglow spectra suggests that the observed H I gas is not local to the GRB progenitor. There are additional lines of evidence for placing the H I gas at distances $\geq 100$ pc from the GRB progenitor. First, one generally detects atomic Mg in the GRB afterglow spectrum. With an ionization potential of $\approx 7.7$ eV, this atom would be fully ionized by the GRB afterglow if the gas were located within ~100 pc of the GRB afterglow (Prochaska et al. 2006). Its detection indicates that the majority of gas lies beyond this distance. Second, one finds that the X-ray spectrum implies larger columns of metals (O and Fe) than observed in the optical spectrum (Watson et al. 2007; Butler et al. 2006). A natural
interpretation of this apparent discrepancy is that the gas probed by X-rays is highly ionized and located near the GRB progenitor, whereas the neutral gas probed by the optical spectrum lies at much larger distances. However, at least four of our sight lines exhibit fine-structure excitation in Si$^+$ and/or Fe$^+$ that indicates UV pumping of excited levels by the UV radiation of the burst. These detections imply that the absorbing material is within $\lesssim 1$ kpc of the burst in which the UV flux is sufficient to excite these transitions. Yet the presence of neutral material implies that $d > 100$ pc. In this range, the intensity of the UV flux of, e.g., GRB 051111, is not sufficient for the photodissociation time of the H$_2$ to be shorter than the time since the afterglow. With the rapid fading of the afterglow, it is unlikely that this intense UV radiation efficiently destroys the H$_2$ on its own, although it may make a non-negligible contribution to the local photodissociating radiation. For these reasons, we will now proceed by interpreting the molecular fractions, ignoring the direct influence of the GRB itself.

4.4. Constraints on the Physical Conditions of GRB-DLAs

Figure 3 shows the LMC, SMC, QSO-DLA, and GRB-DLA molecular fraction patterns compared to model grids calculated with the Browning et al. (2003) H$_2$ radiative transfer code. The models span a range of cloud densities, sizes, and ambient radiation fields, for solar (Fig. 3a), 10% solar (Figs. 3b and 3c), and 1% solar metallicity (Fig. 3d). The models represent the clouds as simple isothermal ($T = 90$ K) slabs of finite extent $d$ in the line of sight that are illuminated on one side by a UV radiation field. These simple assumptions are adequate to study the H$_2$ formation-destruction balance as a function of metallicity and radiation field (Browning et al. 2003).

To explain the reduced abundance of H$_2$ in the MCs compared with the MW, T02 invoked both low metallicity and an elevated radiation field, owing to the robust star formation. Petitjean et al. (2006) have demonstrated the dependence of H$_2$ detection probability on metallicity for QSO-DLAs. In their sample of 41 QSO-DLA systems, they find a 5% rate of detection where metallicity (proxied by Zn, S, or Si) is below 0.05 solar, rising to 50% where the metallicity is $\gtrsim 0.2$ solar. Our result, 0 or 1 detections in five systems, is consistent with the expectation of 1.5 detections on average from the QSO-DLA statistics (although the QSO-DLA sample with systematically lower $N_{\text{HI}}$ is not precisely representative of the GRB-DLAs). This result clearly indicates an important role for metallicity in determining the H$_2$ abundance. The sole effect of metallicity can be seen in Fig. 3c and 3d, using the upper curves for a MW-like interstellar radiation field. At 1% solar metallicity, the molecular fraction curves for the Galactic radiation...
field lie well below those for solar and LMC/SMC metallicity, in agreement with the Petitjean et al. (2006) findings. However, these conditions still imply more H$_2$ than is actually observed, indicating that an extra destruction mechanism, most likely ambient UV radiation, further suppresses the H$_2$.

Though the GRB-DLA detection statistics are consistent with the QSO-DLA systems, accounting for metallicity (but not for higher $N_{H_1}$), the limits on H$_2$ abundance imply additional suppression of H$_2$ when compared with detailed models. The GRB-DLAs have systematically higher $N_{H_1}$ than the QSO-DLAs, only one of which lies above log $N_{H_1}$ = 21.5, where there are three GRB-QSOs. Thus, more $H_2$ is expected for the same conditions, and so comparable limits on $f_{H_2}$ imply different conditions, i.e., more suppression of H$_2$. The effect of the UV radiation is also clearly seen in Figure 3. These models show that if we interpret the destruction of H$_2$ in the GRB-DLAs as being caused by ambient UV irradiation of low-metallicity gas, radiation fields 10–100 times the Galactic mean value are implied (Figs. 3c and 3d). This UV radiation could come from the star-forming region hosting the GRB progenitor, possibly with a minor contribution from the afterglow itself (see § 4.3 above). These UV radiation fields are typical of continuous starbursts of 1–10 $M_\odot$ yr$^{-1}$ at a distance of 1–10 kpc (Leitherer et al. 1999). Thus, the absence of H$_2$ in the GRB-DLAs can be readily explained with the simple hypothesis that the absorbing clouds are illuminated by UV radiation from recently formed hot stars, as was invoked by T02 for the LMC and SMC. It is not necessary to invoke the direct influence of the GRB UV-optical afterglow itself, although it emits copious amounts of UV radiation (Prochaska et al. 2006). Because it can place upper limits to the amount of radiation incident on the absorbing cloud seen as a GRB-DLA, any detection of H$_2$ in such sight lines would be extremely valuable for determining the physical origin of these mysterious absorbers.

5. DISCUSSION AND CONCLUSIONS

We have studied the molecular hydrogen abundances in five GRB-DLA systems and compared them to diffuse molecular gas in local star-forming environments. These GRB-DLAs have some of the highest H column densities known, yet show a surprising lack of H$_2$ when compared with the Milky Way, Magellanic Clouds, and DLAs toward QSOs. This absence of H$_2$ to such low limits is unexpected, given the column densities of H and metallicities of these sight lines. We find no evidence that the GRB itself has affected the absorbing material, and in some cases there is positive evidence that it has not (Prochaska et al. 2007a). We therefore conclude that the absorbing material is likely irradiated by a far-ultraviolet radiation field from massive stars that is 10–100 times more intense than the interstellar field in the solar neighborhood. This conclusion is broadly concordant with the general conclusion that GRBs arise from massive stars in robustly star-forming regions, but the large H i columns and the contrast with analogous local star-forming regions (e.g., 30 Doradus) remain to be explained.

In the ISM of nearby galaxies, carbon monoxide (CO) is used as a tracer of star-forming gas in dense environments. CO can be studied in the diffuse interstellar medium using the UV absorption bands from the ground vibrational state. However, detections are challenging in low column density H$_2$-bearing clouds, even in Galactic material of solar metallicity, which typically shows column density ratios $N_{CO}/N_{H_1} \sim 10^{-7} - 10^{-6}$ for $N_{H_1} \sim 10^{19} - 10^{20}$ cm$^{-3}$ (Burgh et al. 2006). Since the abundance of CO should scale down with metallicity, CO absorption from the low-metallicity GRB-DLAs is certainly not expected. Given the easy photodissociation of CO by UV radiation (van Dishoeck & Black 1988), our result that GRB hosts possess intense FUV radiation fields suggests that CO detections in low-metallicity, star-forming GRB hosts will be extremely challenging. This expectation is corroborated by the recent nondetection of CO emission in the host of GRB 030329 (Endo et al. 2007). We may therefore be left with only indirect far-infrared and millimeter indicators of dusty star-forming gas in high-redshift GRB hosts.

The strong FUV radiation fields inferred for the GRB-DLAs raise the question of whether massive stars are more common in the stellar initial mass function (IMF) in robustly star-forming, low-metallicity galaxies at high redshift. There are theoretical reasons to suspect that the characteristic stellar mass of the IMF increases with decreasing metallicity, owing to reduced cooling efficiency in the gas (Omukai et al. 2005). The characteristic mass may also be increased by the thermal influence of radiation in the star-forming environment (Larson 2005). However, the available star formation indicators for GRB hosts, such as optical nebular emission lines and far-infrared emission from warm dust, only trace massive stars. While some direct or indirect tracer of low- and intermediate-mass stars must be sought to constrain the IMF more directly, the FUV radiation field inferred for these GRB-DLAs certainly imposes a requirement that the IMF must satisfy.

It is difficult to quantify what biases may result from the selection of GRB sight lines by the presence of a bright optical afterglow. To some unknown extent, the GRB-DLAs may represent a special subset of interstellar gas at high redshift. One possible bias is against GRBs that lie behind large column densities of dust, such that they leave no bright optical afterglows that can be studied spectroscopically. Such a system would be likely to show H$_2$ as well. But even the systems studied here show (1) large columns of H i, (2) appreciable dust (Prochaska et al. 2007a), and yet (3) no molecular hydrogen. There is no obvious bias that can select for the first two factors and against the third, so we must interpret these data as if they were fair samples of their ambient ISM. Clearly, larger samples are needed to quantify possible selection biases in the GRB ISM sight lines.

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