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### Article

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## THE DISCOVERY OF VIBRATIONALLY EXCITED H<sub>2</sub> IN THE MOLECULAR CLOUD NEAR GRB 080607

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### ABSTRACT

GRB 080607 has provided the first observational signatures of molecular absorption bands toward any galaxy hosting a gamma-ray burst (GRB). Despite the identification of dozens of features as belonging to various atomic and molecular (H<sub>2</sub> and CO) carriers, many more absorption features remained unidentified. Here, we report on a search among these features for absorption from vibrationally excited H<sub>2</sub>, a species that was predicted to be produced by the UV flash of a GRB impinging on a molecular cloud. Following a detailed comparison between our spectroscopy and static, as well as dynamic, models of H<sub>2</sub>\* absorption, we conclude that a column density of  $10^{17.5\pm 0.2}$  cm<sup>-2</sup> of H<sub>2</sub>\* was produced along the line of sight toward GRB 080607. Depending on the assumed amount of dust extinction between the molecular cloud and the GRB, the model distance between the two is found to be in the range 230–940 pc. Such a range is consistent with a conservative lower limit of 100 pc estimated from the presence of Mg I in the same data. These distances show that substantial molecular material is found within hundreds of pc from GRB 080607, part of the distribution of clouds within the GRB host galaxy.

*Key words:* galaxies: ISM – gamma rays: bursts – ISM: clouds – ISM: molecules – molecular processes

### 1. INTRODUCTION

Long-duration gamma-ray bursts (GRBs) are currently understood to be the electromagnetic manifestation of highly beamed energy from the sites of the demise of young massive stars (see, e.g., Woosley & Bloom 2006). This implies that GRB progenitors must have formed and lived near molecular clouds in their respective host galaxies. Direct evidence for the molecular nature of their birthplace has been lacking, presumably owing to complete destruction of molecules within  $\sim 100$  pc of the GRB (Tumlinson et al. 2007; Whalen et al. 2008). Recently, Prochaska et al. (2009, hereafter P09) presented the first unambiguous spectroscopic detection of absorption bands from H<sub>2</sub> and CO molecules along a translucent GRB sight line (GRB 080607,  $z = 3.0363$ ). Their initial analysis provided the first discovery of molecular gas with properties very similar to those of Galactic molecular clouds, but located in the star-forming ISM of a GRB host galaxy.

The detection by P09 of neutral species (e.g., C I, Mg I) toward GRB 080607 indicates that the bulk of the atomic gas was  $\geq 100$  pc from the GRB, presumably beyond the photoionization sphere formed by the progenitor (Whalen et al. 2008). However, whereas Whalen et al. (2008) introduced an additional galactic-wide far-ultraviolet (FUV) field as a means to suppress the formation of unobserved H<sub>2</sub>, the discovery of more than  $10^{21}$  cm<sup>-2</sup> of H<sub>2</sub> toward GRB 080607, well shielded by dust extinction (rest-frame  $A_V = 3.2$  mag), raises the possibility that the molecular material could have been in close proximity to the GRB. The detection by P09 of absorption from rotationally excited CO, and the determination that atomic and molecular lines are kinematically distinguished by  $30 \pm 15$  km s<sup>-1</sup>, specifically allow for this scenario.

Excitation of fine-structure atomic lines via UV fluorescence is well attested along GRB sight lines (e.g., Fe<sup>+</sup>; Prochaska et al. 2006). Draine (2000), followed by Draine & Hao (2002, hereafter DH02), predicted that observable quantities of vibrationally excited H<sub>2</sub> (from  $v'' > 0$ , hereafter H<sub>2</sub>\*) can be pro-

duced by UV photons in molecular gas within 100 pc from a GRB source. With an assumed model peak luminosity of  $L_0 = 1/40$  of that observed for GRB 990123, DH02 produced a column density ( $N$ ) of  $\approx 10^{19}$  cm<sup>-2</sup> of H<sub>2</sub>\* in a gas with an initial  $N = 10^{21}$  cm<sup>-2</sup> of cold H<sub>2</sub> at close proximity ( $\leq 1$  pc) to the GRB. P09 reported cold H<sub>2</sub> with  $N \approx 10^{21.2}$  cm<sup>-2</sup> toward GRB 080607, suggesting the possibility that H<sub>2</sub>\* could also have been present.

Here, we report on our successful search for absorption from H<sub>2</sub>\* toward GRB 080607. Previously, one Galactic sight line was shown to have  $\sim 500$  absorption lines associated with H<sub>2</sub>\* (Meyer et al. 2001, toward HD 37903), while the sample of low-redshift galaxies, meanwhile, that are found to emit rovibrational H<sub>2</sub>\* lines near  $2.1 \mu\text{m}$  has been increasing steadily, albeit mostly attributed to shocked gas (Thompson et al. 1978; Jaffe & Bremer 1997; Donahue et al. 2000; Dale et al. 2009). Our sight line toward GRB 080607 at the redshift of  $z = 3.0363$  is thus the most distant detection of H<sub>2</sub>\*, as well as the first extragalactic detection of H<sub>2</sub>\* via absorption: this was made possible thanks to an extremely bright GRB, an extremely capable optical system (the LRIS spectrometer on the Keck I telescope), and a rapid response to the GRB alert from *Swift*. We also show, by a comparison with theoretical predictions, that this detection serves to confirm the general picture of the interaction between a GRB and its immediate galactic environment.

### 2. OBSERVATIONS AND MODELING

The acquisition of the spectroscopic data analyzed here was described by P09. Here, we recap some essential information relating to the sequence of events in the rest frame of the GRB, owing to the predicted temporal evolution of the H<sub>2</sub>\* abundance (DH02).

GRB 080607 triggered the *Swift* detector at 06:07:27 UT on 2008 June 7 (Mangano et al. 2008), here defined as  $t = 0$  s. A first series of three Keck/LRIS exposures was taken by us (D.A.P. and J.S.B.) with the B600 and R400 gratings, simultaneously

**Table 1**  
H<sub>2</sub>\* Features Identified Toward GRB 080607

$\lambda_{\text{obs}}$ (Å)	$W_\lambda^a$ (Å)	ID in P09 <sup>b</sup>	$\lambda_{\text{rest}}$ (Å)	ID in DH02 <sup>c</sup>	New ID <sup>d</sup> ( $v''$ ; $J''$ )
5762.6	0.8	...	1427.1	...	(6; 0,1)
5783.5	1.1	...	1432.3	...	(6; 2)
5789.7	0.6	...	1433.8	...	(6; 4)
5797.4	1.4	...	1435.7	P1+R1	(8; 0)
5988.6	1.0	...	1483.1	...	(10; 2)
6002.3	2.6	...	1486.5	R0+R1	(7; 0,1)
6012.5	1.9	...	1489.0	...	(7; 1,2)
6115.3	1.1	UID	1514.5	...	(8; 0,1)
6124.8	1.5	UID	1516.8	R1+P1	(7; 2)
6130.3	1.3	UID	1518.2	P1	(11; 0,1)
6135.6	0.9	...	1519.5	...	(8; 2)
6156.6	0.9	Included in Si II	1524.7	...	(7; 3)
6179.2	0.6	...	1530.3	...	(10; 1)
6205.8	0.6	...	1536.9	...	(10; 3)
6213.8	0.6	...	1538.9	...	(9; 0,1)
6263.7	1.4	Included in C IV	1551.2	...	(12; 1,2)
6269.1	0.6	UID	1552.6	...	(13; 1)
6318.8	0.7	UID	1564.9	...	(13; 1)
6414.3	0.9	Included in Si I	1588.6	R0+R1	(10; 0,1)
6432.1	0.7	UID	1593.0	...	(10; 2)
6477.4	1.6	UID	1604.2	...	(9; 1)
6489.1	1.5	Included in Fe II	1607.1	P1+R3	(9; 2)
6525.8	0.6	...	1616.2	...	(12; 5)
6604.4	0.7	Included in Fe II	1635.7	...	(9; 1)
6614.6	1.6	Included in Fe II	1638.2	R1+R2	(11; 2)

#### Notes.

<sup>a</sup> Detections with  $W_\lambda \geq 0.6 \text{ \AA}$  ( $\geq 4\sigma$ ).

<sup>b</sup> UID: listed in P09 without ID. Otherwise, was included in a stronger atomic feature.

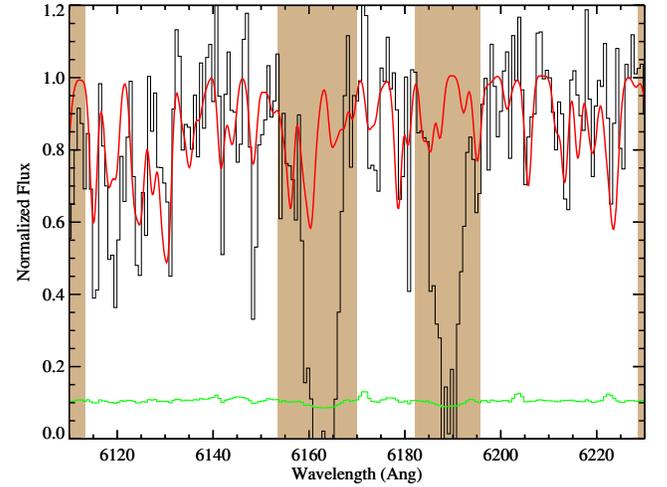
<sup>c</sup> Strongest transitions within  $1.0 \text{ \AA}$  of  $\lambda_{\text{rest}}$  for  $R = 350$ .

<sup>d</sup> Strongest contributing ro-vibrational levels for  $R = 4000$ .

employing the blue and red cameras. These exposures were 75, 150, and 300 co-moving seconds long, centered on rest-frame times  $t = 340, 490,$  and  $730$  s. A second series of two exposures was taken with the B600 and R1200 gratings, both 370 s long, and centered on the post-trigger times  $t = 1230$  and  $1640$  s in the rest frame of the GRB. In terms of spectral resolution, the subarcsecond seeing resulted in  $\lambda/\Delta\lambda = R \sim 4000, 2000,$  and  $1000,$  for gratings R1200, B600, and R400, respectively.

Our initial search for possible H<sub>2</sub>\* features involved spectral syntheses of relevant transitions with the Y.S. code Ismod.f, and comparisons with the highest- $R$  data from the R1200 grating. Each transition was modeled with a single Voigt profile, employing as fixed parameters the resolution  $R$ , transition rest wavelength ( $\lambda_{\text{rest}}$ ) and oscillator strength ( $f$ -value), the Doppler parameter  $b$ , and a radial velocity of  $+30 \text{ km s}^{-1}$  relative to the atomic gas (P09). Both the  $\lambda_{\text{rest}}$  and  $f$ -values for  $B$ - $X$  and  $C$ - $X$  transitions of H<sub>2</sub>\* were downloaded from the MOLAT Web site<sup>6</sup> (E. Roueff 2009, private communication). Table 1 lists our H<sub>2</sub>\* identifications for 25 absorption features detected at the  $\geq 4\sigma$  level in the R1200 spectrum.

Once we were convinced of the presence of (static) H<sub>2</sub>\* absorption in the data toward GRB 080607, we shifted to full dynamic modeling, with photoexcitation, photodissociation, and photoionization of the gas treated following DH02. The UV and X-ray emission from GRB 080607 was assumed to be



**Figure 1.** Zoomed comparison between the Keck/LRIS R1200 data (black histogram) and the H<sub>2</sub>\* dynamic model (smooth red line). Brown masking designates absorption from other identified species (e.g., Si II at 6163 and 6189 Å), where the detection of H<sub>2</sub>\* would be compromised by blending. The agreement is very good between stronger H<sub>2</sub>\* absorption features and equally strong, hitherto unidentified “lines” in the spectrum. The noise level is denoted by the green line at the bottom.

described by

$$\nu L_\nu = L_0 \left( \frac{h\nu}{13.6 \text{ eV}} \right)^{1+\beta} \frac{4(t/t_0)^2}{[1 + (t/t_0)^2]^2}, \quad (1)$$

where  $L_0 = 5 \times 10^{50} \text{ erg s}^{-1}$ ,  $\beta = -0.5$ , and  $t_0 = 10$  s. With  $A_V = 3.2$  mag (P09), this reproduces the observed  $K$ -band flux density at  $t_{\text{obs}} = 300$  s. The value of  $L_0$  is 200 times higher than that adopted in DH02. Indeed, GRB 080607 ranks among the most powerful to date, an equal to GRB 990123 in  $\gamma$  luminosity (Golenetskii et al. 2008).

Total line-of-sight abundances for H and H<sub>2</sub> were taken from P09, with the H nucleon density ( $n_{\text{H}}$ ) taken to be  $10^3 \text{ cm}^{-3}$ . The dust/gas ratio in the pre-GRB gas was assumed to be  $\sim 10\%$  of the local Milky Way value (P09). For photoexcitation of the H<sub>2</sub> and photoionization of H and H<sub>2</sub>, we were primarily interested in the dust extinction cross section per H nucleon at  $\lambda < 1110 \text{ \AA}$ , which we take to be  $\sigma = 2 \times 10^{-22} \text{ cm}^2$ , so that  $A_{1000\text{\AA}} = 5.33 \times 10^{22} \times 2 \times 10^{-22} / 1.086 = 9.8$  mag, or  $A_{1000\text{\AA}}/A_V = 3.1$ .

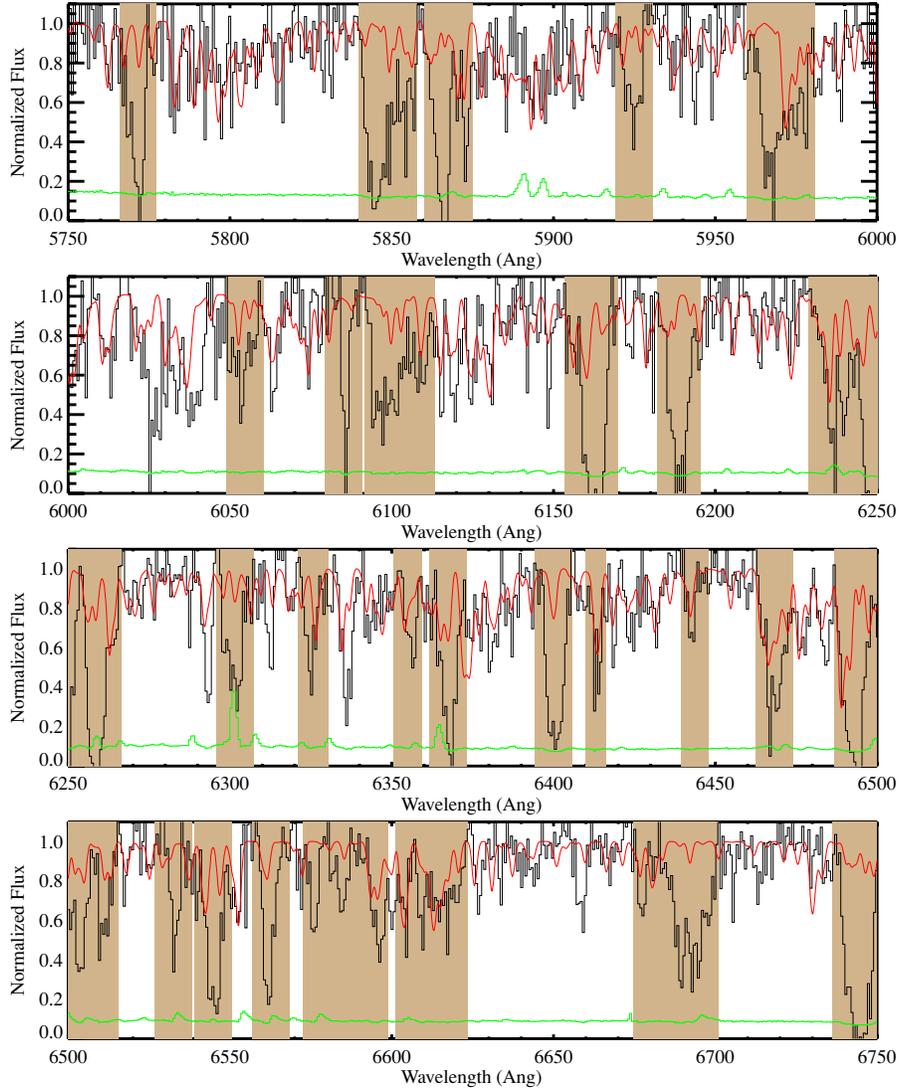
Finally, the evolution of the irradiated dust was followed with the same assumptions as in DH02. Initial grain size was  $a = 0.04 \text{ \mu m}$ , which could decrease by thermal sublimation if the grains became hot enough. For calculating UV extinction we used  $Q_{\text{ext}} = 2$ , where  $Q_{\text{ext}}$  is the ratio of the extinction cross section to the geometric cross section,  $\pi a^2$ .

## 3. RESULTS AND DISCUSSION

### 3.1. H<sub>2</sub>\* Column Density

Figure 1 shows a small portion of the R1200 data, superposed by 336 modeled transitions of H<sub>2</sub>\*. This region includes five absorption “lines” that were listed, but not identified, in P09, four of them as a group between  $\lambda_{\text{obs}} = 6115$ – $6130 \text{ \AA}$ . However, each H<sub>2</sub>\* “line” is a blended feature that includes several strong transitions. It is evident that the four observed features near  $6120 \text{ \AA}$  are too strong to be attributed to noise: their equivalent width ( $W_\lambda$ ) values listed in P09 range over  $1.1$ – $2.3 \text{ \AA}$ , or  $7$ – $15$  times the  $1\sigma$  detection limit. Since these “lines” cannot be identified with any other plausible atomic or molecular species, at the redshift of either GRB 080607 or the two intervening

<sup>6</sup> <http://molat.obspm.fr/>



**Figure 2.** Same as Figure 1, but showing 1000 Å of the R1200 data and the model of H<sub>2</sub>\*. Dozens of narrow H<sub>2</sub>\* and observed features appear to agree with each other. The global pattern of variable  $v' - v''$  band strength is also matched.

absorption systems, we are confident that H<sub>2</sub>\* provides the only viable model for their presence in our data. For the best match with the data, the static modeling with Ismod.f returned  $\log N(\text{H}_2^*) = 17.7 \pm 0.3$ , using  $b = 2 \text{ km s}^{-1}$ , a value taken from the CO analysis of P09. Our full dynamic modeling with the DH02 code, computing H<sub>2</sub> excitation for  $10^3 \text{ s}$  in the GRB time frame and using  $b = 3 \text{ km s}^{-1}$ , returned  $\log N(\text{H}_2^*) = 17.5 \pm 0.2$ , in good agreement with the static model. This served to confirm that the first case of H<sub>2</sub>\* excitation by GRB photon pumping has been identified.

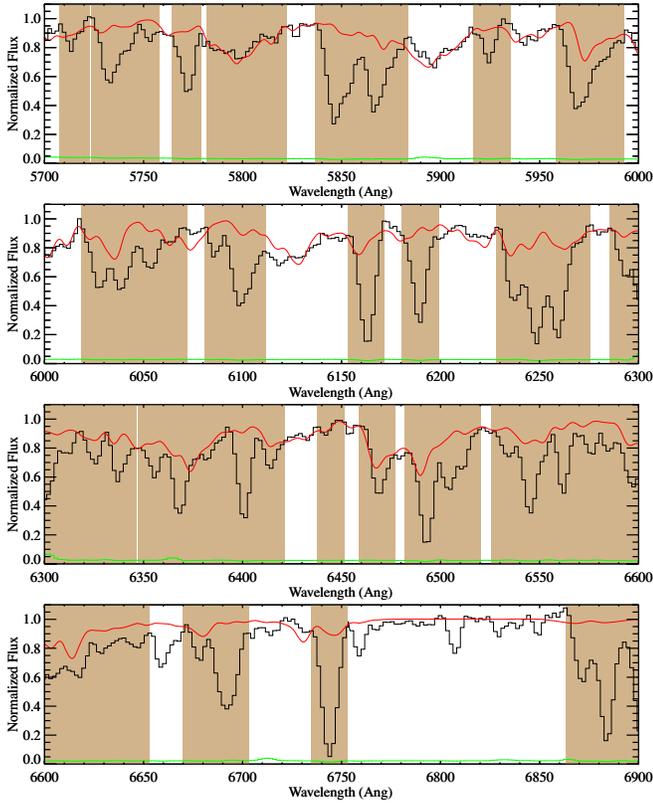
The entire range of the R1200 spectrum ( $\lambda_{\text{rest}} = 1400\text{--}1720 \text{ \AA}$ ) covers the red portion of H<sub>2</sub>\* absorption, and includes 3372 transitions with  $J'' = 0\text{--}29$ ,  $v'' = 1\text{--}14$ , and  $v' = 0\text{--}16$ . Figure 2 presents a global view of the H<sub>2</sub>\* model spectrum superposed over 1000 Å of the R1200 data. The overall agreement between data and model is acceptable, given that the  $S/N \approx 10$  and the presence of numerous other absorption features from, e.g., host-galaxy CO bandheads and Fe II from two foreground absorbers (P09). The few instances where the modeled absorption is significantly deeper than the data involve levels with  $v'' \geq 9$ , presumably related to our incomplete description (underestimation) of UV photoionization rates out of high- $v''$  levels.

We identified 25 narrow H<sub>2</sub>\* features that are the least blended with other species and list these in Table 1. Previously, P09 estimated atomic abundances in the weak limit from the measured  $W_\lambda$  of absorption features. Since some transitions listed in P09 are seen here (Figure 2) to be blended with some of the stronger H<sub>2</sub>\* features, certain  $W_\lambda$  values should be revised downward. For example, the H<sub>2</sub>\* feature at 6466 Å falls into a blend with the Ge II 1602 line, contributing 2.0 Å to the total  $W_\lambda$  of 5.3 Å and reducing its weak-limit abundance (estimated by P09 to be super-solar). However, only a future detailed study of sight-line saturation will be able to provide robust abundance determinations based on H<sub>2</sub>\*-corrected data.

The presence of H<sub>2</sub>\* in our R1200 spectrum is confirmed by the lower signal-to-noise ratio (S/N) exposures from the B600 grating ( $R = 2000$ ). In all, the blue and red gratings provide  $\sim 500 \text{ \AA}$  of rest-frame coverage of numerous absorption features belonging to (or blended with) H<sub>2</sub>\* toward GRB 080607.

### 3.2. H<sub>2</sub>\* Variability Versus Nonvariability

The theoretical work of DH02 followed the temporal behavior of H<sub>2</sub>\* abundance in response to the initial UV flash from a GRB afterglow. Upon photoexcitation into the electronic *B* and *C* states, only  $\sim 15\%$  of H<sub>2</sub> is photodissociated, with the



**Figure 3.** Same as Figure 2, but showing the lower-resolution R400 data and  $H_2^*$  model. Absorption from wide features made up of numerous  $H_2^*$  transitions is determining the shape of the continuum of the R400 spectrum. Some absorption features previously assigned to atomic carriers are clearly significantly blended with contribution from  $H_2^*$ .

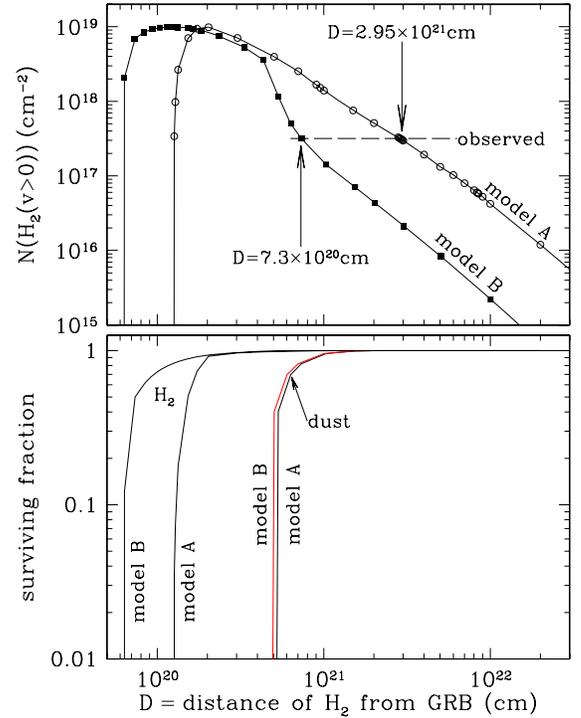
majority, therefore, decaying immediately into  $v > 0$  levels of the  $X$  ground state. A very rapid rise in  $N(H_2^*)$  occurs over the timescale of the burst ( $\approx 10$  s) as the UV photons get absorbed by the cold  $H_2$  gas. The  $10^6$  s lifetime of  $H_2^*$  (Draine 2000) means that it remains around for almost two months in the observer frame.

As described in Section 2, our two groups of red exposures were centered on  $t \sim 500$  and 1400 s in the GRB rest frame. As shown in Figure 3, a degraded  $R = 1000$  version of the  $H_2^*$  model that matches the R1200 spectrum shows remarkable agreement with the upper envelope of the R400 spectrum. Thus, there is no indication of variation in  $N(H_2^*)$  over the  $\Delta t \sim 900$  s that elapsed between the clusters of R400 and R1200 exposures. This observational result confirms the DH02 theoretical predictions that  $N(H_2^*)$  varies over timescales that are either significantly shorter or significantly longer than those covered by our observations.

### 3.3. The Distance of $H_2^*$ from the GRB

The value of  $N(H_2^*)$  detected here is only  $\sim 3\%$  of that produced by the models in DH02. According to DH02, the amount of  $H_2^*$  produced depends on the fluence,  $F$ , of the source, and hence on the ratio  $L_0/D^2$ , where  $D$  is the distance from the GRB to the center of the initial  $H_2$  integration zone. Owing to the much higher value of  $L_0$  used in our modeling of GRB 080607 (Section 2), the production of an appreciably smaller amount of  $H_2^*$  relative to DH02 would require a very large increase in  $D$ .

We employ the detailed modeling of DH02 in order to explore the dependence of  $N(H_2^*)$  on  $D$ . The effect of the GRB on the



**Figure 4.** Column density of vibrationally excited  $H_2$  as a function of distance from GRB 080607, for two models differing in the location of the H I relative to the  $H_2$  (see the text).

$H_2$  will depend on what fraction of the H I is located between the GRB and the  $H_2$ , because the dust in the H I gas can help shield the  $H_2$  from photons with  $\lambda < 1110$  Å, and the H I itself will help protect the  $H_2$  from photoionization.

We consider two cases. Model A has  $N(H^0) = 2 \times 10^{21} \text{ cm}^{-2}$  located between the GRB and the  $H_2$ , with the remainder of the H I located beyond the  $H_2$ . Model B has  $N(H^0) = 5 \times 10^{22} \text{ cm}^{-2}$  (i.e., all of the H I detected by P09) located between the GRB and the  $H_2$ . For a given large value of  $D$ , model B will have less UV-pumped  $H_2$  than model A, because of the additional dust shielding in model B. However, for smaller values of  $D$ , reduced shielding by the destruction of dust and H I in model B may result in complete destruction of the  $H_2$  by photodissociation or photoionization.

The upper panel of Figure 4 shows  $N(H_2^*)$  versus  $D$  for the two models. The observed value of  $\approx 10^{17.5} \text{ cm}^{-2}$  (Section 3.1) is generated for  $D = 2.9 \times 10^{21}$  or  $7.3 \times 10^{20} \text{ cm}$  for Model A or B, respectively. Thus, we conclude that the  $H_2$  in GRB 080607 is located between 230 and 940 pc from GRB 080607, a value much larger than that used in DH02 ( $D \ll 1$  pc).

The lower panel of Figure 4 shows the fraction of the initial dust and  $H_2$  that survives after the GRB flash. For more than 50% of the initial grain mass to be sublimated, the  $H_2$  gas would have to be within  $\sim 190$  pc, slightly closer than the location of the  $H_2^*$  in model B, and substantially closer than in model A. We conclude that for these two models, the bulk of the dust survives the GRB flash, consistent with  $A_V \approx 3.2$  mag observed during the afterglow phase. Substantial destruction of the  $H_2$  by a combination of photodissociation and photoionization occurs only for  $D < 2 \times 10^{20} \text{ cm} = 65$  pc. Given the observed  $N(H_2^*)/N(H_2) \approx 10^{-3.7}$ , we conclude that there has been minimal destruction of  $H_2$  in the cloud where the  $H_2^*$  resides.

More complex models are of course possible: if more than one  $H_2$  cloud is present, there could have near-complete destruction of the  $H_2$  in the inner cloud, leaving only a small amount of  $H_2$

with high levels of vibrational excitation, with the bulk of the H<sub>2</sub> in a more distant cloud with little vibrational excitation.

### 3.4. What about CO\*?

The presence of H<sub>2</sub>\* prompted us to search for vibrationally excited CO (CO\*) in our data. P09 reported the detection of  $\log N = 16.5 \pm 0.3 \text{ cm}^{-2}$  of cold ( $v'' = 0$ ) CO, all of which was rotationally- excited (hereafter r-CO\*) at  $T_{\text{ex}} \sim 300 \text{ K}$  up to  $J'' = 25$ . If the vibrational excitation of CO owing to UV pumping scales with that of H<sub>2</sub>, then we should expect  $\log N(\text{CO}^*) = \log N(\text{CO}) - 3.7 \approx 12.8 \text{ cm}^{-2}$ . CO\* transitions for  $v'' > 0$  bands were taken from Kurucz line lists<sup>7</sup> and modeled with Ismod.f, but no match with the R1200 data was found. Based on the strongest  $v'' = 1$  band at 6400 Å, a feature with  $N(\text{CO}^*) = 1 \times 10^{13} \text{ cm}^{-2}$  would have a depth of 10%, comparable to the  $1\sigma$  noise level in the data.

We note that the photophysical behavior of CO differs from that of H<sub>2</sub> in two important respects. First, owing to the existence of strongly predissociating Rydberg states in CO below  $\lambda_{\text{rest}} = 1100 \text{ Å}$  (Letzelter et al. 1987; van Dishoeck & Black 1988; Sheffer et al. 2003), CO\*/CO should be much lower than H<sub>2</sub>\*/H<sub>2</sub>. Second, CO\* spontaneously decays via dipole transitions with a lifetime of ca.  $10^{-2} \text{ s}$  (Okada et al. 2002), roughly  $10^8$  times faster than the quadrupole transitions of H<sub>2</sub>\*. Any small amount of surviving CO\* would be rapidly converted into r-CO\*. However, while CO photophysics may explain the absence of CO\* toward GRB 080607, the challenge of accounting for the conversion of the bulk of cold CO into r-CO\* remains.

Both dust extinction and cold H<sub>2</sub> provide very effective UV shielding of CO below  $\lambda_{\text{rest}} = 1100 \text{ Å}$ , allowing it to survive in deeper layers of a cloud. The nondissociating  $A - X$  bands (with  $v' \leq 8$ ) are significantly less shielded: the data toward GRB 080706 (Figure 1 of P09) show that the UV flux level at  $\lambda_{\text{rest}} > 1322 \text{ Å}$  is  $\sim 5$  times higher than at  $\lambda_{\text{rest}} < 1150 \text{ Å}$ . UV pumping into the CO A state could result in its complete conversion into CO\* and then into r-CO\*. However, assuming that initially the CO is cold ( $T_{\text{ex}} \sim 11 \text{ K}$ ,  $J'' \leq 5$ ), the production of r-CO\* that happens to maintain a quasi-thermal distribution at  $\sim 300 \text{ K}$  up to  $J'' = 25$  must be considered a coincidence of indirect excitation.

Radio observations show that collisionally excited r-CO\* can be found in Galactic photodissociation regions (PDRs; Tielens & Hollenbach 1985), with  $T_{\text{ex}} \sim 100\text{--}1000 \text{ K}$  (van Dishoeck & Black 1988; Draine & Bertoldi 1996; Hollenbach & Tielens 1997). This range agrees with  $T_{\text{ex}} \sim 300 \text{ K}$  for r-CO\* toward GRB 080607, subject to the caveat that appreciably higher values of  $N(\text{CO})$  and  $A_V$  are found in Galactic PDRs. We surmise that the r-CO\* toward GRB 080607 could be a pre-burst observational signature of the PDR produced by the progenitor of the GRB, as it was forming a giant H II region around itself (Whalen et al. 2008). A detailed calculation of this process is clearly warranted.

## 4. CONCLUDING REMARKS

In addition to providing the first positive detection of H<sub>2</sub> bands and the first observation of CO bands in a GRB host galaxy (P09), we have shown that GRB 080607 also provides the first evidence for H<sub>2</sub>\* in a GRB host galaxy and marks the highest-redshifted H<sub>2</sub>\* detected to date.

This discovery of UV-pumped H<sub>2</sub>\* toward GRB 080607 serves to confirm the predictions for its production under precisely such circumstances (Draine 2000, DH02). Our initial static modeling with Ismod.f indicated  $\log N(\text{H}_2^*) < 18.0$  toward GRB 080607, significantly lower than the original predictions of DH02. We then showed that the dynamic models of DH02 can successfully reproduce observed H<sub>2</sub>\* absorption once modifications involving individual GRB luminosities and adjustable distance to the molecular cloud are incorporated. Thus, the DH02 photoexcitation code shows that the bulk of the molecular cloud harboring H<sub>2</sub>\* is located at a model distance of 230–940 pc along the line of sight from the UV afterglow. This is much farther than the original arrangement in DH02, but still in the local galactic neighborhood of GRB 080607. In the scheme of Whalen et al. (2008), a model distance of  $> 230 \text{ pc}$  for the molecular cloud means that it is located outside the  $\approx 100 \text{ pc}$  radius of H II region carved by the progenitor of GRB 080607.

One interesting result of the increased distance from the GRB to the gas is the inability of the radiation beam to destroy dust embedded in the cloud. Whereas in DH02 dust was easily destroyed at close quarters to the GRB, following its heating to 2000–3000 K, this process cannot operate at larger distances, leading to survival of the dust in the cloud. Such dust remains on the line of sight between the GRB and the H<sub>2</sub> destruction front, diminishing the effects of such destruction.

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