H$_2$ Absorption and Fluorescence from Gamma Ray Bursts in Molecular Clouds

B.T. Draine

Princeton University Observatory, Peyton Hall, Princeton, NJ 08544; draine@astro.princeton.edu

ABSTRACT

If a gamma ray burst with strong UV emission occurs in a molecular cloud, there will be observable consequences resulting from excitation of the surrounding H$_2$. The UV pulse from the GRB will pump H$_2$ into vibrationally-excited levels which produce strong absorption at wavelengths $\lambda \lesssim 1650$ Å. As a result, both the prompt flash and later afterglow will exhibit strong absorption shortward of 1650 Å, with specific spectroscopic features. Such a cutoff in the emission from GRB 980329 may already have been observed by Fruchter et al.; if so, GRB 980329 was at redshift $3.0 \lesssim z \lesssim 4.4$. BVRI photometry of GRB 990510 could also be explained by H$_2$ absorption if GRB 990510 is at redshift $1.6 \lesssim z \lesssim 2.3$. The fluorescence accompanying the UV pumping of the H$_2$ will result in UV emission from the GRB which can extend over days or months, depending on parameters of the ambient medium and beaming of the GRB flash. The 7.5–13.6 eV fluorescent luminosity is $\sim 10^{41.7}$ ergs s$^{-1}$ for standard estimates of the parameters of the GRB and the ambient medium. Spectroscopy can distinguish this fluorescent emission from other possible sources of transient optical emission, such as a supernova.

Subject headings: galaxies: ISM – gamma rays: bursts – molecular processes – ISM: clouds – ISM: molecules

1. Introduction

At least some gamma ray bursts (GRBs) are accompanied by intense optical emission, as demonstrated by detection of a 9th magnitude optical transient coinciding with GRB 990123 (Akerlof et al. 1999) and optical afterglows associated with other GRBs (e.g., GRB 990510: Stanek et al. 1999; Israel et al. 1999). Since GRBs may be associated with star-forming regions (Paczyński 1998), it is of interest to consider observable phenomena which would be indicative of molecular gas in the vicinity of the GRB. Here we show that there may be both observable absorption and emission due to H$_2$ within several parsecs of a GRB.

The energy radiated in the optical-UV flash and afterglow can be substantial, and can have dramatic effects on interstellar gas and dust in the vicinity of the GRB. The $h\nu > 13.6$ eV emission
will photoionize the gas, and the pulse of optical radiation will vaporize dust grains out to substantial distances from the GRB (Waxman, Draine & Phinney 1999). The gamma-rays and hard X-rays emitted by the GRB will contribute to ionization of the nearby gas, but the UV and soft X-rays have the dominant effect because of the much larger number of photons, and much larger photoionization cross sections.

Ultraviolet radiation will destroy H$_2$ in the vicinity of the GRB, but before destruction the typical H$_2$ molecule will be excited to a vibrationally excited state by UV pumping. While cold molecular hydrogen can absorb only at wavelengths $\lambda < 1110$ Å, this vibrationally-excited H$_2$ can absorb strongly at wavelengths as long as 1650 Å. The characteristic wavelength-dependent absorption by this vibrationally-excited H$_2$ should be imprinted on the spectrum of the optical-UV flash when it reaches distant observers. Subsequent UV emission from the “afterglow” would also be subject to this characteristic absorption, due to vibrationally-excited H$_2$ generated by the initial UV pulse plus additional UV from the afterglow.

In addition to imposing a characteristic absorption spectrum on the optical transient, the optical-UV flash will generate fluorescent UV emission from surrounding H$_2$. Because of light-travel time delays, the fluorescent emission will appear to extend over perhaps tens of days. The emission is strong enough that it could be detectable, and it would have a characteristic spectrum which would distinguish it from other possible sources of optical-UV emission.

2. Photoexcitation of H$_2$

Prior to the GRB, the surrounding H$_2$ is almost entirely in the first two or three rotational levels ($J = 0, 1, 2$) of the ground vibrational level ($v = 0$) of the ground electronic state ($X^1\Sigma_g^+$). To photoexcite to the $B^1\Sigma_u^+$ and $C^1\Pi_u^+$ states requires $h\nu > 11.2$ and 12.3 eV, respectively. To photoionize H$_2$ out of $X^1\Sigma_g^+$($v = 0, J = 0$) requires $h\nu > 15.4$ eV. The cold H$_2$ itself is therefore essentially transparent to $h\nu < 11.2$ eV photons – the dominant absorption for $h\nu < 11.2$ eV is due to dust mixed with the H$_2$.

The first UV photons to arrive will most likely photoexcite the H$_2$ via Lyman or Werner band transitions to the B or C electronic states, or photoionize the H$_2$ to H$_2^+$. H$_2$ which is photoexcited to the B or C states will decay (in $\sim 10^{-9}$ s) back to the ground electronic state, but typically to a vibrationally-excited level (e.g., $v = 5$) with the rotational quantum number changed by $\Delta J = 0, \pm 2$. The lifetimes of the vibrationally-excited levels ($\sim 10^6$ s) are long compared to the timescale for photoexcitation or photoionization [$\sim 10^{-3}$ s – see eq.(2,6,5)], so that depopulation of the rovibrationally-excited levels of H$_2$ will be primarily by UV photoexcitation and photoionization.

If the luminosity of the GRB pulse in 7.5–13.6 eV photons is $10^{49} L_{49}$ ergs s$^{-1}$, and the spectrum $L_\nu \propto \nu^{-1/2}$ as expected from simple models for emission from the forward shock (see Waxman, Draine, & Phinney 1999), then at a distance $10^{19} R_{19}$ cm from the GRB the specific energy density
\( u_\nu \) is given by

\[
\nu u_\nu = 4 \times 10^{-14} \chi \left( \frac{1000 \, \text{Å}}{\lambda} \right)^{1/2} \text{ergs cm}^{-3},
\]

where

\[
\chi = 1.1 \times 10^{13} L_{49} R_{19}^{-2}
\]

is the intensity at 1000Å relative to the Habing (1968) estimate for the local interstellar radiation field.

Stimulated emission in the UV transitions is negligible provided \( \chi \ll 10^{19} \), so we consider photoexcitation out of level \( i \) of \( X^1 \Sigma_g^+ \) to vibration-rotation states of \( B^1 \Sigma_u^+ \) and \( C^1 \Pi_u^\pm \), followed by spontaneous decay to level \( j \) of \( X^1 \Sigma_g^+ \). Let \( T_{ji} \) be the rate for photopumping out of level \( i \) into level \( j \), and let \( \zeta_i^{(pd)} \) and \( \zeta_i^{(pi)} \) be the rates for photodissociation and photoionization out of level \( i \). Spontaneous decay via quadrupole transitions can be neglected if \( \chi \gg 10^4 \), and collisional deexcitation can be neglected if \( n_H / \text{cm}^{-3} \ll \chi \). If

\[
T_{ii} = - \left[ \sum_{j \neq i} T_{ji} + \zeta_i^{(pd)} + \zeta_i^{(pi)} \right],
\]

then the \( \text{H}_2 \) abundances \( p_i \equiv 2n(\text{H}_2(v_i, J_i))/n_H \) evolve according to

\[
\frac{d}{dt}p_i = \sum_j T_{ij}p_j.
\]

We consider the 299 bound states of \( \text{H}_2 \) with \( J \leq 29 \), and construct photopumping rates as described by Draine & Bertoldi (1996), using Lyman and Werner band oscillator strengths and dissociation probabilities from Abgrall et al. (1993a,b) and Roueff (1993). We neglect attenuation of the radiation field due to absorption by \( \text{H}_2, \text{H}, \) or dust. The rate of absorption of Lyman or Werner band photons for \( \text{H}_2 \) in the \( v = 1, J = 3 \) level (for example), is

\[
\zeta_j^{(\text{pexc.})}(v = 1, J = 3) = 3.34 \times 10^{-10} \chi \, \text{s}^{-1},
\]

with a probability \( p_d \approx 0.15 \) of photodissociation.

If Lyman continuum radiation is present, then the \( \text{H}_2 \) photoionization cross section from Yan, Sadeghour, & Dalgarno (1998) yields a photoionization rate

\[
\zeta_j^{(pi)} = 1.96 \times 10^{-10} \chi \, \text{s}^{-1},
\]

which we take to be independent of rovibrational excitation. We will also consider the case where all the Lyman continuum has been absorbed, so that \( \zeta_j^{(pi)} = 0 \).

For the photoionization rate of (6), the probability of returning to a bound rovibrational state following a photon absorption event is

\[
\alpha = (1 - p_d) \zeta_j^{(\text{pexc.})}/(\zeta_j^{(\text{pexc.})} + \zeta_j^{(pi)}) \approx 0.54,
\]

the probability of ultimately being destroyed by photodissociation (rather than photoionization) is
\[ p_d \zeta_j^{(\text{pexc.})} / (p_d \zeta_j^{(\text{pexc.})} + \zeta_j^{(\text{pi})}) \approx 0.20, \text{ and the mean number of fluorescent photons emitted per H}_2 \text{ destroyed by radiation is} \]

\[ N_{\text{fl}} = \frac{1}{(1 - \alpha)} - \frac{\zeta_j^{(\text{pi})}}{p_d \zeta_j^{(\text{pexc.})} + \zeta_j^{(\text{pi})}} \approx 1.36, \]  

including transitions to the vibrational continuum of X1\Sigma_g^+. If, however, the illuminating spectrum is cut off at the Lyman limit, then \( \zeta_j^{(\text{pi})} = 0 \), and \( N_{\text{fl}} \approx 6.7 \) – about 5 times as many fluorescent photons as for the case where Lyman continuum is present.

A detailed study of the H\(_2\) photoexcitation would require modelling the time-dependent spectrum of the radiation as it advances through the cloud. For a preliminary estimate of the rovibrational excitation we neglect changes in the spectrum of the UV pulse, and simply assume the H\(_2\) to be irradiated by the spectrum (1), with and without Lyman continuum radiation. We assume the H\(_2\) to be “cold” at \( t = 0 \), with \( p_j(0) = 0.5 \) for \((v, J) = (0,0)\) and \((0,1)\), and we follow the evolution of the level populations \( p_j(t) \) in the presence of the radiation field (1) until negligible H\(_2\) remains (\( \sum p_j < 10^{-6} \)). We compute the time-integrated level populations \( P_j = \int_0^\infty p_j dt \). In Figure 1 we show the normalized level populations \( \phi_j \equiv P_j / \sum_j P_j \) versus level energy \( E_j \). We see that even with Lyman continuum radiation, the time-averaged level populations have \( \sim 50\% \) of the H\(_2\) in vibrationally-excited levels; if photoionization is suppressed, however, \( \sim 70\% \) of the H\(_2\) is in levels \( v \geq 1 \).

### 3. Photoabsorption by UV-pumped H\(_2\)

Waxman, Draine & Phinney (1999) discuss the destruction of dust by the GRB flash, and estimate the dust destruction radius to be \( R_d \approx 2.5 \times 10^{19} \text{ cm} \) for a \( \sim 10 \text{ sec} \) pulse with luminosity \( L_{49} \approx 0.55 \), and density \( n_H \lesssim 10^5 \text{ cm}^{-3} \). Since we will estimate below that the radial extent of UV-pumped H\(_2\) will be considerably smaller than \( R_d \), it seems likely that dust destruction will take place so rapidly (in the leading edge of the GRB optical pulse) that we can neglect the effects of dust absorption and scattering when considering the excitation and destruction of the H\(_2\).

Photoexcitation by the GRB optical pulse produces rovibrationally excited H\(_2\) with permitted absorption lines in the 912 – 1650 Å region. Figure 2 shows the absorption, smoothed to a resolution \( R = \lambda / \Delta \lambda = 100 \), produced by column densities \( N(\text{H}_2) = 10^{16}, 10^{18}, \text{ and } 10^{20} \text{ cm}^{-2} \) with the distributions \( \phi(v, J) \) from Figure 1. We assume Voigt profiles, approximated following Rodgers & Williams (1974), with Doppler broadening parameter \( b = 3 \text{ km s}^{-1} \), for the 28765 permitted Lyman and Werner band lines between levels with \( J \leq 29 \). It is clear that the rovibrationally-excited H\(_2\) absorbs quite strongly for \( \lambda \lesssim 1650 \text{ Å} \) (\( h\nu \gtrsim 7.5 \text{ eV} \)): for \( N(\text{H}_2) \approx 10^{18} \text{ cm}^{-2} \), it can be seen from Figure 2 that approximately 1/3 of the energy between 1650 and 912 Å has gone into photoexcitation of H\(_2\). In the discussion below we will assume that all of the photons between 1650 and 912 Å are available for photoexcitation of H\(_2\).
The energy radiated in the afterglow may be comparable to or even exceed that emitted in a few tens of seconds around the emission peak. Let \( N_{\text{ion}} \) be the total number of \( h\nu > 13.6 \text{ eV} \) photons, and \( N_{\text{uv}} \) be the total number of 7.5–13.6 \text{ eV} photons. For the \( F_\nu \sim \nu^{-1/2} \) spectrum observed for the afterglow of GRB 990510 (Stanek et al. 1999) and expected from simple models (e.g., Waxman, Draine, & Phinney 1999), \( N_{\text{uv}}/N_{\text{ion}} = 0.35 \).

Dust within \( \sim 2.5 \times 10^{19} \text{ cm} \) of the GRB will be vaporized by \( h\nu < 7.5 \text{ eV} \) photons in the initial flash, so dust absorption will be neglected for the \( h\nu > 7.5 \text{ eV} \) photons of interest here. In an infinite cloud, the GRB will fully ionize the hydrogen and helium within a radius

\[
R_{\text{ion}} \approx 1.5 \times 10^{19} \left( \frac{E_{50}}{n_3} \right)^{1/3} \text{ cm},
\]

where \( n_3 \equiv n_\text{H}/10^3 \text{ cm}^{-3} \), the total energy in 7.5–13.6 \text{ eV} photons is \( 10^{50}E_{50} \) ergs, and we have assumed \( n_{\text{He}}/n_\text{H} = 0.1 \). For \( r < R_{\text{ion}} \) we will suppose that 20% of the \( \text{H}_2 \) is destroyed by photodissociation rather than by photoionization, (absorbing \( N_{\text{fl}} = 1.36 \text{ UV photons per photodissociation} \) thus absorbing a fraction \( 0.2N_{\text{fl}}(0.5N_{\text{ion}}/1.2)/N_{\text{uv}} = 0.33 \) of the 7.5–13.6 \text{ eV} photons at \( r < R_{\text{ion}} \). The remaining 67% of the UV photons will photodissociate \( \text{H}_2 \), with a probability \( p_d \approx 0.15 \) per absorption, and therefore will dissociate the \( \text{H}_2 \) out to a radius

\[
R_{\text{H}_2} \approx R_{\text{ion}} \left( 1 + \frac{0.15 \times 0.67(N_{\text{uv}}/0.5)}{N_{\text{ion}}/1.2} \right)^{1/3} = 1.027R_{\text{ion}}.
\]

The column density of this photodissociation zone is \( n_\text{H}(R_{\text{H}_2} - R_{\text{ion}}) = 4 \times 10^{20}n_3^{2/3}E_{50}^{1/3} \text{ cm}^{-2} \).

A more accurate treatment must simultaneously model photodissociation of the \( \text{H}_2 \), photoionization of \( \text{H} \), \( \text{H}_2 \), and \( \text{He} \), and attenuation of the radiation field by these absorption processes. This is particularly critical since we estimate \( R_{\text{H}_2} \approx R_{\text{ion}} \). For the present, however, we can safely conclude that not all the 7.5–13.6 \text{ eV} photons which can pump \( \text{H}_2 \) will have been absorbed by the radius \( R_{\text{ion}} \) where all of the \( h\nu > 13.6 \text{ eV} \) photons are exhausted. Therefore there will be a shell of rovibrationally excited \( \text{H}_2 \) outside \( R_{\text{ion}} \). Since the linear extent of the zone of partially-dissociated (and therefore rovibrationally excited) \( \text{H}_2 \) is determined by the attenuation length for the 1650–912\text{Å} photons which can photodissociate the \( \text{H}_2 \), Fig. 2 would suggest that this layer of partially-dissociated (and rovibrationally-excited) \( \text{H}_2 \) would have a column density \( N(\text{H}_2) \approx 10^{20} \text{ cm}^{-2} \), and therefore a linear extent \( \Delta R \approx 2 \times 10^{17}n_3^{-1} \text{ cm} \). Because the vibrationally-excited levels have lifetimes \( \gtrsim 10^6 \text{ s} \) against spontaneous decay, and collisional deexcitation is negligible for \( n_3 \lesssim 10 \), the vibrational excitation in the layer of partially-dissociated \( \text{H}_2 \) will persist for weeks after the GRB.

Attenuation by the rovibrationally-excited \( \text{H}_2 \) will produce a strong “jump” near 1650\text{Å} in the spectrum of both the optical flash and the afterglow. The absorption is due to many distinct absorption lines, as is evident if the spectrum is shown with a resolution \( R = 1000 \), as in Figure 3.

Fruchter (1999) found that the spectrum of the GRB 980329 optical transient showed a strong drop in flux between I (9000\text{Å}) and R (6600\text{Å}). Fruchter interpreted this drop as due to Lyman
α (λ = 1215 Å) absorption at redshift z ≈ 5, with the Lyman forest then suppressing the flux at shorter wavelengths. However, recent deep imaging and spectroscopy of the host galaxy indicate that it must be at z < 5, and probably z < 4 (Djorgovski et al. 1999). If GRB 980329 occurred in a molecular region, the observed drop in flux between I and R could have been due to the onset of H$_2$ absorption at 1650 Å in the host galaxy, in which case GRB 980329 was at redshift $3.0 \lesssim z \lesssim 4.4$.

Stanek et al. (1999) reported that VRI photometry of the afterglow of GRB 990510 were described by $F_\nu \propto \nu^{-0.46 \pm 0.08}$, but the B band flux falls below this prediction, indicating either a deviation from power-law behavior in the source, or additional extinction either near the GRB or in an intervening galaxy. Here we note that rovibrationally-excited H$_2$ could account for this if the redshift of GRB 990510 is in the interval $1.6 \lesssim z \lesssim 2.3$, so that the 1650 Å absorption “edge” falls between B and V. This redshift for GRB 990510 is not inconsistent with the detection of absorption lines at $z = 1.62$ (Vreeswijk et al. 1999a,b).

4. H$_2$ Fluorescence

As seen above, most of the $6.5 - 13.6$ eV photons emitted by a GRB in a molecular cloud will be absorbed by H$_2$. A fraction of the photoexcitations will result in photodissociation, but approximately 80% of the absorbed energy will be reradiated in UV fluorescent emission.

Waxman, Draine & Phinney (1999) have shown that the prompt optical flash will result in destruction of the dust within $\sim 10$ pc of the GRB. If the observer is situated in the “beam” of the optical flash, then the fluorescent emission can reach the observer along a path from which the dust has been cleared, out to a distance $R_d \approx 10$ pc. There will be some attenuation of the fluorescent emission by H$_2$ absorption, but such absorption is relatively weak for $\lambda \gtrsim 1300$ Å (see Figure 2).

If the prompt optical flash is radiated into a cone with half-width $\theta \approx 0.1$ (for a beaming factor $4\pi/\pi\theta^2 \approx 400(0.1/\theta)^2$), then the fluorescent emission from a shell of radius $R$ will reach the observer spread out over a time $\Delta t_{H_2fl} \approx R\theta^2/c \approx 39{(R/10^{19}\text{ cm}){(\theta/0.1)}^2}$ days. Because $\Delta t_{H_2fl}$ is long compared to the GRB flash, for purposes of estimating the light curve of the fluorescent emission we can approximate the flash itself as a delta function.

Suppose that a fraction $f(r)$ of the H$_2$ at radius $r$ is destroyed by the prompt flash, with fluorescent energy $\epsilon$ emitted per destroyed H$_2$ molecule. If the observer is situated along the beam axis, then the fluorescent emission from regions with time delay $< t$ is

$$E_\nu(t) = \pi\epsilon_\nu\theta^2 \int_0^{ct/\theta^2} f(r)n(H_2)r^2dr + \pi\epsilon cct \int_{ct/\theta^2}^{\infty} f(r)n(H_2)rdr$$

If we now assume that $n(H_2)$ is independent of radius, and $f(r) = 1$ for $r < R_{H_2}$, and 0 for $r > R_{H_2}$, then the apparent luminosity is

$$(\nu L_\nu)_{H_2fl} = \frac{dE_\nu}{dt} = \frac{\pi}{2}\nu\epsilon_\nu n(H_2)R_{H_2}^2 c \left(1 - \frac{\nu^2\theta^4}{R_{H_2}^2}\right)$$
\[ \nu \nu = 2.4 \times 10^{41} \left( \frac{\nu \nu}{10^{-10} \text{ergs}} \right) n_3 \left( \frac{R_{\text{H}_2}}{10^{19} \text{cm}} \right)^2 \left\{ 1 - \left[ \left( \frac{t}{39 \text{ days}} \right) \left( \frac{10^{19} \text{cm}}{R_{\text{H}_2}} \right) \left( \frac{0.1}{\theta} \right)^2 \right]^2 \right\} \text{ergs s}^{-1}. \]

We have computed the fluorescence spectrum \( \nu \nu \) for \( \text{H}_2 \) being destroyed by continuum radiation with \( I_\nu \propto \nu^{-1/2} \), both with and without a cutoff at 912 Å; the results are shown in Figure 4. The emitted radiation is concentrated in the 1650 – 912 Å (7.5–13.6 eV) range. The values of \( \nu \nu \) differ by a factor \( \sim 5 \), but according to our estimate, \( \sim 90\% \) of the destroyed \( \text{H} \) is in the photoionized zone, so \( \nu \nu \approx 1 \times 10^{-10} \text{ergs/H}_2 \) is a representative average. There will be some “self-absorption” of this emission by the rovibrationally-excited \( \text{H}_2 \) itself, an effect not included in the present analysis. If this fluorescent emission has also to traverse cold \( \text{H}_2 \), it will suffer additional absorption, but only in a small number of absorption lines between 1110 and 912 Å.

The fluorescent emission estimated in eq. (12) appears to be a necessary consequence of a GRB in a molecular region. It is intriguing to note that the estimated luminosity and timescale are comparable to what would emerge from a supernova, although the spectrum of course is very dissimilar.

Since the emission is concentrated between 1650 – 912 Å, this process could not account for the emission plateau observed \( \sim 20 – 30 \) days after GRB980326 (Bloom et al. 1999) unless the redshift \( z \approx 3.5 \) (so that the 1600–1000 Å emission would be redshifted to 7200–4500 Å). However, at \( z = 3.5 \) the observed \( F_\nu = 0.4 \mu \text{Jy} \) at R would require \( \nu L_\nu = 2 \times 10^{44} \text{ergs s}^{-1} \) (for \( \Omega = 0.3 \), \( H_0 = 70 \text{ km s}^{-1} \text{Mpc}^{-1} \)), or \( n_3^{1/2} E_{50} \approx 5000 \), much larger than anticipated for standard parameters \( (n_3 \approx 1, E_{50} \approx 1) \). Furthermore, the spectrum obtained by Bloom et al. 28 days after the GRB does not appear consistent with a redshifted version of Figure 4. For GRB980326, then, it does not appear likely that the observed emission plateau is due to \( \text{H}_2 \) fluorescence; the \( z \approx 1 \) supernova hypothesis proposed by Bloom et al. appears much more plausible.

However, \( \text{H}_2 \) fluorescence could perhaps be seen in other GRBs. GRBs at \( z \approx 1.5 \) – so that the 1600 Å emission peak is redshifted to \( \sim 4000 \text{Å} \) – offer the best prospect for detection of this fluorescent emission, although it would still be quite faint for nominal parameters: \( (F_\nu)_{\text{max}} \approx 2.5 \times 10^{-9} n_3 (R_{\text{H}_2}/10^{19} \text{cm})^2 \text{Jy} \) at 4000 Å.

5. Discussion

The GRB pulse will create a large amount of \( \text{H}_2^+ \) mixed with surviving \( \text{H}_2 \) in the partially-dissociated shell. In these regions \( \text{H}_3^+ \) will be formed on a timescale \( \sim 10^6 (10^3 \text{cm}^{-3}/n(\text{H}_2)) \) s. This \( \text{H}_3^+ \) will promptly react to produce other species, e.g., \( \text{H}_3^+ + \text{CO} \rightarrow \text{HCO}^+ + \text{H}_2 \). The millimeter-wave lines of \( \text{HCO}^+ \) and other species might be observable in absorption against the afterglow, although this would probably require that the redshift first be determined by other methods (e.g. the \( \text{H}_2 \) absorption lines discussed here).
Perna & Loeb (1998), Ghisellini et al. (1998), and Böttcher et al. (1998) have previously called attention to time-varying atomic and ionic absorption lines and X-ray absorption edges expected for GRBs, and Ghisellini et al. and Böttcher et al. pointed out that time-varying Fe K-α fluorescence might be observable from GRBs. Perna, Raymond & Loeb (1999) have pointed out that atomic and ionic emission lines might be observable from the photoionized remnants left behind by GRBs in relatively nearby galaxies.

Observations of any of these phenomena would provide valuable clues to the nature of GRBs and their environments. If GRBs occur in molecular regions, the relatively strong H₂ absorption spectrum may offer the best observational prospects for GRBs at redshift \(z \gtrsim 1.3\) so that \(\lambda \approx 1650\ \text{Å}\) is accessible to ground-based spectrographs.

### 6. Summary

The principal conclusions of this paper are:

- Ultraviolet emission from a GRB will produce vibrationally-excited H₂ which will produce strong line absorption for \(1650 \gtrsim \lambda \gtrsim 912\ \text{Å}\). This absorption signature should be imprinted on the spectrum of the radiation reaching us from GRBs in molecular regions.

- Absorption by vibrationally-excited H₂ could be responsible for the pronounced drop in flux between R and I for GRB 980329 (Fruchter 1999), if GRB 980329 is at \(3.0 \lesssim z \lesssim 4.4\).

- Absorption by vibrationally-excited H₂ could account for the drop in flux between V and B for GRB 990510 (Stanek et al. 1999), if GRB 990510 is at \(1.6 \lesssim z \lesssim 2.3\).

- Ultraviolet emission from a GRB will produce fluorescent emission from whatever H₂ may be present within tens of parsecs of the GRB. This fluorescence is potentially observable [see eq. (12) and Fig. 4].

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Fig. 1.— Time-averaged fraction of the irradiated H$_2$ in different vibration-rotation states, versus energy of the level, for an irradiating spectrum $I_\nu \propto \nu^{-1/2}$, with intensity $10^5 \ll \chi \ll 10^{19}$. For a typical GRB flash with $L_{49} \approx 1$ we estimate $\chi \approx 10^{13}$ [see eq. (2)]. Collisional processes are neglected, valid for $n_H \lesssim 10^{-3}\chi \text{cm}^{-3}$. Upper panel shows results for irradiation with cutoff at 912 Å; lower panel shows result if there is no break at the Lyman limit.
Fig. 2.— Transmission through a medium with $\text{H}_2$ which has been rovibrationally excited by UV pumping by radiation with $I_\nu \propto \nu^{-1/2}$ and an intensity $10^5 \ll \chi \ll 10^{19}$ relative to the Habing intensity. Transmission, smoothed to a resolution $R = 100$, is shown for column densities $N(\text{H}_2) = 10^{16}$, $10^{18}$, and $10^{20}$ cm$^{-2}$ with the level populations of Fig. 1.
Fig. 3.— Same as Fig. 2, but with resolution $R = 1000$. 
Fig. 4.— Fluorescent emission $\nu E_\nu$ per irradiated $\text{H}_2$ molecule, for irradiation by $I_\nu \propto \nu^{-1/2}$ with cutoff at 912 Å (upper panel), or including Lyman continuum (lower panel).