A DETECTION OF MOLECULAR GAS EMISSION IN THE HOST GALAXY OF GRB 080517

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ABSTRACT

We have observed the host galaxy of the low-redshift, low-luminosity Swift GRB 080517 at 105.8 GHz using the IRAM Plateau de Bure interferometer. We detect an emission line with integrated flux \( \Delta \nu = 0.39 \pm 0.05 \) Jy km s\(^{-1}\)—consistent both spatially and in velocity with identification as the \( J = 1 \rightarrow 0 \) rotational transition of carbon monoxide (CO) at the host galaxy redshift. This represents only the third long gamma-ray burst (GRB) host galaxy with molecular gas detected in emission. The inferred molecular gas mass, \( M_{\text{H}_2} \sim 6.3 \times 10^8 M_\odot \), implies a gas consumption timescale of \( \sim 40 \) Myr if star formation continues at its current rate. Similar short timescales appear characteristic of the long GRB population with CO observations to date, suggesting that the GRB in these sources occurs toward the end of their star formation episode.

Key words: galaxies: individual (GRB Host 080517) – gamma-ray burst: individual (GRB 080517) – radio lines: galaxies

1. INTRODUCTION

Long gamma-ray burst (GRB) host galaxies are selected out by the explosion that is believed to mark the end of the life of a massive star (e.g., Woosley & Heger 2006). Given the short lifetime of such stars, it is unsurprising that the vast majority of host galaxies to date have been identified as star forming (e.g., Savaglio et al. 2009; Svensson et al. 2010) and are predicted to be rich in molecular gas (Draine & Hao 2002; Draine 2000). The absence of absorption signatures in the afterglows of bursts, illuminating molecular gas along their line of sight out of their host galaxy, has thus caused some concern. Initial investigations (e.g., Vreeswijk et al. 2004; Ledoux et al. 2009) revealed a shortage of detections in the \( \text{H}_2 \) Lyman–Werner bands relative to those expected. Unusually low-metallicity, low-dust content conditions, preventing the formation of molecules on the surface of dust grains, have been invoked as a possible content conditions, preventing the formation of molecules on the surface of dust grains, have been invoked as a possible

2. OBSERVATIONS

Observations, centered on the X-ray location of GRB 080517 (\( 06^248^m 58^s03 +50^544^07^7, 105.8 \) GHz), were undertaken at the IRAM Plateau de Bure Interferometer (PdBI) on 2014 June 9 and 2014 June 11. The WideX correlator was used to probe a 3.6 GHz bandwidth centered at 105.8 GHz, the expected frequency of the CO(1–0) transition at the target redshift, at 2 MHz resolution. Data were collected by observatory staff and scheduled across hour angles ranging from \( -4.1 \) to 1.2 hr to ensure good \( \nu \)-plane coverage. A total integration time of 72 minutes was achieved on target. The array was in the compact 5Dq configuration, with five antennae in use. The resulting synthesized beam had a FWHM of \( 5.7 \times 4.4^\prime \) and a half-power width of the PdBI primary beam at this frequency is 48\'. Band-pass and flux calibration was performed on 3C454.3, yielding an estimated systematic uncertainty \( <10\% \). Phase calibration was performed with reference observations of QSO B0714+457, which has a flux of 0.2 Jy at these frequencies, taken at regular intervals throughout the science observing. Data were reduced and calibrated using standard tools in the GILDAS data reduction package, and were imaged using natural weighting.

A flux excess was observed in the resulting data cube at the pointing center and target frequency. We extract spectral information from a spatial region corresponding to 1.5 times the synthesized beam. The center of this aperture is located at

\( z = 0.089 \pm 0.003 \)

GRB host galaxy, with evidence for a mature stellar population underlying an ongoing star formation episode (Stanway et al. 2014). The host galaxy is accompanied by a neighboring galaxy, sufficiently close in velocity and projected distance to plausibly be interacting with it. In this Letter we present observations targeting the \( J = 1 \rightarrow 0 \) rotational transition of carbon monoxide in this system.\(^4\)

We have recently identified the host of GRB 080517 as an example of an unusually low-redshift (\( z = 0.089 \pm 0.003 \)) GRB host galaxy, with evidence for a mature stellar population underlying an ongoing star formation episode (Stanway et al. 2014). The host galaxy is accompanied by a neighboring galaxy, sufficiently close in velocity and projected distance to plausibly be interacting with it. In this Letter we present observations targeting the \( J = 1 \rightarrow 0 \) rotational transition of carbon monoxide in this system.\(^4\)

\(^4\) Based on observations carried out with the IRAM Plateau de Bure Interferometer. IRAM is supported by INSU/CNRS (France), MPG (Germany) and IGN (Spain).
the optical position of the GRB 080517 host galaxy (i.e., within 2" of the pointing center). As Figure 1 illustrates, the resulting spectrum shows a clear emission line centered at 105.790 GHz. This corresponds to \( z = 0.08962 \pm 0.00003 \) if the line is identified, as we expect, as the CO \( J=1-0 \) rotational transition with a rest-frame frequency of 115.271 GHz.

We re-imaged the data, integrating those channels contributing to the line, yielding a total bandwidth of 40 MHz (113 km s\(^{-1}\)). The resulting image (Figure 2) reveals an isolated source located coincident with the optical center of the GRB host galaxy. Deconvolution with the synthesized beam yields a marginally resolved source with FWHM 2.0 \( \times \) 2.5 prime, consistent with the 1.7 Sersic radius measured in the optical (although with considerable uncertainty since this source is well below the size of the synthesized beam).

The observed emission line has a peak flux 7.7 \( \pm \) 1.7 mJy, measured in a 4 MHz channel. A Gaussian fit to the observed line yields a FWHM of 76.5 km s\(^{-1}\) and an integrated line flux \( S\Delta v = 0.39 \pm 0.05 \) Jy km s\(^{-1}\) (a 7\( \sigma \) detection). A possible second velocity component is observed at a velocity offset of \( \sim -170 \) km s\(^{-1}\), but at too low a significance to be considered a detection (2\( \sigma \)). No 2.8 mm continuum flux is detected from the GRB host galaxy to a 3\( \sigma \) limit of 0.4 mJy beam\(^{-1}\) in a map constructed from line-free channels, with a total bandwidth of 3.4 GHz.

The neighboring galaxy described in Stanway et al. (2014) is offset from the GRB host by 16" and \( \Delta v = 576 \pm 155 \) km s\(^{-1}\), allowing us to simultaneously constrain it with this data. Neither line nor continuum flux is detected from the neighboring galaxy to the limits of the data. We note that one component of the neighbor (Component B in Stanway et al. 2014) is coincident to the limits of the data. We convert the integrated line flux obtained above to a CO luminosity:\(^{5}\) The resulting line luminosity, \( L_{\text{CO}} = 1.5 \times 10^{8} \) K km s\(^{-1}\) pc\(^2\), corresponds to an inferred molecular gas mass, \( M_{\text{H}_2} = \alpha L_{\text{CO}} = 6.3 \times 10^{6} M_{\odot} \) for the Galactic conversion factor \( \alpha = 4.3 M_{\odot}/(K \text{ km s}^{-1} \text{ pc}^2) \) (Bolatto et al. 2013; Prochaska et al. 2009). This amounts to only 15% of stellar mass derived from spectral energy distribution (SED) fitting (Stanway et al. 2014).

### 3. Inferred Quantities

We convert the integrated line flux obtained above to a CO luminosity:\(^{5}\) The resulting line luminosity, \( L_{\text{CO}} = 1.5 \times 10^{8} \) K km s\(^{-1}\) pc\(^2\), corresponds to an inferred molecular gas mass, \( M_{\text{H}_2} = \alpha L_{\text{CO}} = 6.3 \times 10^{6} M_{\odot} \) for the Galactic conversion factor \( \alpha = 4.3 M_{\odot}/(K \text{ km s}^{-1} \text{ pc}^2) \) (Bolatto et al. 2013; Prochaska et al. 2009). This amounts to only 15% of stellar mass derived from spectral energy distribution (SED) fitting (Stanway et al. 2014).
et al. 2014) and potentially less if the $\alpha = 0.8$ conversion factor appropriate for densely star forming systems such as ULIRGs is more appropriate.

Given a measured luminosity in the CO(1–0) line, we can estimate the likely far-infrared luminosity, assuming that the host galaxy follows the well-established (see Solomon & Vanden Bout 2005, and references therein) correlation between these quantities. The inferred $L_{\text{FIR}} = 2 \times 10^{10} L_{\odot}$ would correspond to a predicted 105.8 GHz continuum flux of just 8 $\mu$Jy, assuming a modified blackbody with dust temperature 35 K and emissivity index $\beta = 2.0$, consistent with our non-detection in the continuum. Given this modified blackbody spectrum, the predicted submillimeter flux at 850 $\mu$m (350 GHz) would be $S_{\text{850}} = 0.8$ mJy, challenging but within reach of the current generation of instruments.

Interestingly, we can compare this prediction for the submillimeter luminosity with estimates based on earlier observations. The $H\alpha$ and 22 $\mu$m-continuum derived star formation rate (SFR) of $\sim 16 M_{\odot} \text{ yr}^{-1}$ (Stanway et al. 2014) would lead to a predicted thermal infrared luminosity $L_{\text{FIR}} \sim 10^{11} L_{\odot}$, while the radio continuum emission detected at 4.5 GHz would suggest a thermal infrared luminosity $L_{\text{FIR}} \sim 6 \times 10^{9} L_{\odot}$ (using conversions from Kennicutt & Evans 2012). The estimate from the carbon monoxide line emission is bracketed by these alternate estimates. Given that each conversion from flux to SFR is associated with a $\sim 30\%$ error, and that the scatter in the $L_{\text{CO}} - L_{\text{FIR}}$ relation is $\sim 0.5$ dex, these results show broad agreement, producing a coherent picture of the emission from ongoing star formation and its associated gas supply within the GRB 080517 host galaxy.

4. DISCUSSION

Detections of GRB host galaxies in molecular gas are rare, at least in part because of the difficulty of such observations, but the remarkable feature of the host of GRB 080517 is not its detection, but rather that the emission is so weak. The inferred molecular gas mass in the GRB host represents less than $20\%$ of the stellar mass derived from its optical and near-infrared continuum flux. While this gas fraction is not, in itself, unusual, in combination with the galaxy’s SFR it presents an anomaly.

The ongoing SFR in the host galaxy of GRB 080517 is higher than typical for its stellar mass and suggests that it will burn through its available supply of molecular gas in $\sim 40$ Myr, assuming $100\%$ conversion of gas to stars. More conservative estimates for the efficiency of molecular gas conversion only reduce this timescale. The short implied gas consumption timescale suggests that the host of GRB 080517 is undergoing a short-lived star formation episode which is unlikely to add significantly to its stellar mass. This conclusion is consistent with the results of fitting the optical-near infrared SED, which required that the ongoing starburst contributed $< 1\%$ of the mass of the host galaxy, which is dominated by a more mature, 500 Myr old stellar population (Stanway et al. 2014).

The width of the observed CO(1–0) emission line may lend tentative support to such a scenario. If the line width, $\Delta v = 77$ km s$^{-1}$, is interpreted as Doppler broadening due to the stellar velocity dispersion, it implies a virial mass of just $1.3 \times 10^{10} M_{\odot}$. This must include the SED-derived stellar mass, $3.8^{+0.2}_{-0.2} \times 10^{9} M_{\odot}$ (Stanway et al. 2014) and the gas content. The fraction of molecular relative to atomic gas in GRB host galaxies is poorly constrained, with existing measurements suggesting $\sim 10\%$ (Frisi et al. 2014; Krühler et al. 2013) or lower (D’Elia et al. 2014) based on individual lines of sight probed by ultraviolet spectra of GRB afterglows. Our estimated molecular gas mass $M_{\text{H}_2} \sim 6 \times 10^8 M_{\odot}$ would therefore imply an atomic gas content similar to the galaxy’s stellar mass. Comparison with the virial mass suggests either that the host galaxy has very little dark matter, or that the line emission is not fully sampling the stellar velocity dispersion, as would be the case in a highly inclined disk galaxy or if the emitting gas has been recently accreted onto the GRB host and is not yet virialized.

Given the presence of a neighboring galaxy, itself star-forming and sufficiently close in both projection and velocity to constitute an interacting system (Stanway et al. 2014; Ellison et al. 2008), it is tempting to speculate that the gas supply was accreted during a recent near fly-by of the galaxy pair. However, we caution that the current data has neither the signal to noise nor the spatial resolution to identify tidal features or other direct evidence of gravitational interaction. Alternate explanations remain plausible. There is evidence that the CO(1–0) transition may be sub-thermally excited in some galaxies with modest SFRs (e.g., Daddi et al. 2014) at $z > 1$. These are typically higher in redshift and specific SFR and lower in metallicity than GRB Host 080517 (Stanway et al. 2014). Measurement of further rotational emission lines will be required to determine an accurate spectral line excitation ladder, and hence accurate gas temperature and mass.

Star formation in the local universe is usually seen in relatively low-mass galaxies compared to those at higher redshifts—the well-known “downsizing” phenomenon (Cowie et al. 2004). Where star formation is observed in massive galaxies, it is typically accompanied by large molecular gas reserves. As a result the timescale for depletion of molecular gas, $\tau = M_{\text{H}_2}/$ SFR in years, scales with the stellar mass of a galaxy (Bothwell et al. 2014).

As Figure 3 demonstrates, the estimated gas mass and SFR places the host galaxy of GRB 080517 on the established gas-to-specific SFR relation (main sequence) for star forming galaxies in the local universe, but well away from the predicted gas consumption timescale for its mass (Saintonge et al. 2011b; Bothwell et al. 2014). For comparison, we also mark the locations in this parameter space of those burst hosts with comparable CO measurements (Hatsukade et al. 2011, 2014; Endo et al. 2007), drawing stellar mass and SFR estimates from the literature (Perley et al. 2013; Michalowski et al. 2009) where necessary. We exclude the host of $z \sim 8$ burst GRB 090423 since it remains undetected in the continuum (Berger et al. 2014; Tanvir et al. 2012), as well as in molecular gas emission (Stanway et al. 2011).

The host of GRB 080517 appears to be typical of those GRB hosts observed to date. These all show short gas depletion timescales below the relation derived by Bothwell et al. (2014) and Saintonge et al. (2011b) for star forming galaxies in the local universe. This is somewhat puzzling as a straightforward interpretation would imply that GRBs typically occur toward the end of a star formation episode, when little molecular gas remains. Such an interpretation contrasts with the assumption that they arise from massive stars, which collapse with only a short delay after the onset of star formation. An alternate plausible scenario is that the starburst giving rise to the GRB in these sources is a short-lived “flash in the pan” event, not contributing substantially to the galaxy mass, as would seem to be the case for GRB 080517. This too would be a little surprising, since it implies that all the bursts observed in molecular gas to date fall into this category with the bulk properties of the host.
all literature values to our assumed CO-H$_2$ conversion factor, et al. (2009). It has been suggested that may be due in part studies of GRB afterglows (see Tumlinson et al. 2007; Ledoux galaxy not representative of the brief star formation episode 2011a) and ALLSMOG (Bothwell et al. 2014) surveys. The dashed line marks 080517, compared to local galaxies from the COLDGASS (Saintonge et al. Figure 3. Timescale for molecular gas consumption (in years) for GRB Host τ = M(H$_2$) / SFR (yr). We note that our analysis represents an independent con- σsSFR / yr$^{-1}$ for gas consumption in this system ($\sim 40$ Myr) and, together with constraints from other wavelengths, suggest that the GRB occurred in a short-lived star formation episode that does not dominate the galaxy’s mass. It appears that the GRB host galaxies observed to date show lower gas masses than might be anticipated from their mass and SFR, implying that building this sample in future may be difficult. While GRB 080517 is too far north for follow-up observations with ALMA, we have demonstrated that it is accessible with older, northern hemisphere arrays and that similar galaxies may be straightforwardly probed with current instrumentation. A.J.L. and E.R.S. are funded in part by STFC grant ST/L000733/1. The research leading to these results has received funding from the European Commission Seventh Framework Programme (FP/2007-2013) under grant agreement No. 283393 (RadioNet3). We are very grateful to the PdBI staff observers and schedulers who secured good $uv$-plane coverage in this short integration.

Facility: IRAM:Interferometer

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5. CONCLUSIONS

We have identified only the third long GRB host galaxy to show observed emission from molecular gas. The integrated emission line flux of GRB host 080517, $S\Delta v = 0.39 \pm 0.05$ Jy km s$^{-1}$, suggests an estimated molecular mass of $M_{H_2} \sim 6.3 \times 10^8 M_\odot$. This leads to a remarkably short timescale for gas consumption in this system ($\sim 40$ Myr) and, together with constraints from other wavelengths, suggest that the GRB occurred in a short-lived star formation episode that does not dominate the galaxy’s mass.

galaxy not representative of the brief star formation episode underlying the burst. We note that our analysis represents an independent confirmation of the molecular gas deficit seen in absorption line studies of GRB afterglows (see Tumlinson et al. 2007; Ledoux et al. 2009). It has been suggested that may be due in part to the low metallicity typical of burst hosts (Tumlinson et al. 2007; Ledoux et al. 2009) with resultant low dust content, or that detection of H$_2$ absorption requires significant depletion of refractory elements onto dust grains (Krühler et al. 2013), although the small spatial scales probed by absorption studies along a line of sight complicate these interpretations (Friis et al. 2014). It seems unlikely that metallicity is a strong factor in the short gas consumption timescales seen in Figure 3. While all five bursts appear consistent with shorter timescales than typical for their mass, GRBs 980425 and 000418 are believed to be sub-solar in mean metallicity, while GRBs 020819B, 051022, and 080517 are likely solar or super-solar (see Stanway et al. 2014; Hatsukade et al. 2014; Levesque et al. 2010; Svensson et al. 2010).

On the other hand, the role of depletion of metals onto dust grains may be significant. Of the bursts with CO detections, or deep limits, to date; GRBs 051022 and 020819B are classified as “dark” bursts, their optical afterglows likely sub-luminous due to dust extinction (see Perley et al. 2013), and GRBs 080517 and 000418 show evidence for dusty conditions in their host galaxy (080517, Stanway et al. 2014) or afterglow (000418, Klose et al. 2000). The host of the low-redshift, low-luminosity GRB 980425, by contrast, is characterized by a low dust content overall, but with a high-density environment associated with the GRB site (Michalowski et al. 2014). All five GRB hosts investigated to date therefore have dust properties somewhat atypical of the GRB population as a whole (see, e.g., Svensson et al. 2010). Characterizing any association between extinction and gas depletion timescales will require larger, more complete samples. Obtaining these may be possible in the near future, utilizing the new sensitivity of ALMA for southern hemisphere targets. However, our observations with the (five element) PdBI demonstrates that detections of low-redshift GRB hosts are possible with more moderate instrumentation.
