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Published in:
Astrophysical Journal

DOI:
10.3847/1538-4357/acd74f

Publication date:
2023

Document version
Publisher's PDF, also known as Version of record

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Citation for published version (APA):
Main Sequence to Starburst Transitioning Galaxies: Gamma-Ray Burst Hosts at $z \sim 2$

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Received 2022 December 6; revised 2023 May 19; accepted 2023 May 19; published 2023 July 21

Abstract
Star-forming galaxies populate a main sequence (MS), a well-defined relation between stellar mass ($M_*$) and star formation rate (SFR). Starburst (SB) galaxies lie significantly above the relation, whereas quenched galaxies lie below the sequence. In order to study the evolution of galaxies on the SFR–$M_*$ plane and its connection to the gas content, we use the fact that recent episodes of star formation can be pinpointed by the presence of gamma-ray bursts (GRBs). Here we present sensitive $[\text{C}\,\text{I}]$ nondetections of $z \sim 2$ ultraluminous infrared (ULIRG) GRB host galaxies. We find that our GRB hosts have similar molecular masses to those of other ULIRGs. However, unlike other ULIRGs, the GRB hosts are located at the MS or only a factor of a few above it. Hence, our GRB hosts are caught in the transition toward the SB phase. This is further supported by the estimated depletion times, which are similar to those of other transitioning galaxies. The GRB hosts are $[\text{C}\,\text{I}]$-dark galaxies, defined as having a $[\text{C}\,\text{I}]/$CO temperature brightness ratio of $<0.1$. Such a low $[\text{C}\,\text{I}]/$CO ratio has been found in high-density environments ($n_{\text{H}_2} > 10^4 \text{ cm}^{-3}$) where CO is shielded from photodissociation, leading to underabundances of $[\text{C}\,\text{I}]$. This is consistent with the merger process that is indeed suggested for our GRB hosts by their morphologies.

Unified Astronomy Thesaurus concepts: Gamma-ray bursts (629); Gamma-ray sources (633); Galaxies (573); Starburst galaxies (1570); Quenched galaxies (2016)

1. Introduction
Star formation occurs in molecular gas clouds (Wong & Blitz 2002; Gao & Solomon 2004a; Bigiel et al. 2008; but see Glover & Clark 2012; Krumholz 2012; Michałowski et al. 2015). The molecular gas fraction and its availability for star formation are key ingredients that shape the evolution of galaxies (see review by Saintonge & Catinella 2022) and determine the place where a galaxy is found in the star formation rate (SFR)–stellar mass ($M_*$) plane. Normal star-forming galaxies (SFGs) form a well-defined “main sequence” (MS) on this plane with a scatter of about 0.2 dex (Birnbaum et al. 2004; Noeske et al. 2007; Speagle et al. 2014).

The so-called starburst galaxies are found above the MS with extremely high SFRs for a given stellar mass (Combes et al. 2011; Rodighiero et al. 2011; Larson et al. 2016). It is not clear whether an increase in star formation efficiency (SFE; Cheng et al. 2018; Hogan et al. 2022) or gas mass fraction (Lee et al. 2017; Valentino et al. 2020a) drives the departure from the MS. As pointed out by Gao & Solomon (2004b), the global SFR depends mainly on the amount of dense molecular gas, which can be traced for example by a hydrogen cyanide (HCN) line. This dependence remains nearly the same (with a slope of about 1) for normal and starburst galaxies, including ultraluminous galaxies (ULIRGs). The HCN observations however are limited to the local universe due to the weakness of this line. Thus, until deep HCN (or other dense gas tracers) observations are available, we need to rely on other approximations.

Major and minor mergers have been invoked as possible causes for triggering the starburst behavior (Combes et al. 2011; Rodighiero et al. 2011; Larson et al. 2016; Saintonge & Catinella 2022). Eventually, some galaxies will terminate their star formation. These galaxies tend to have red colors, compact and spheroidal morphologies (Schawinski et al. 2014; Nadolny et al. 2021), with relatively low gas and dust content.

Most of the information on molecular gas in galaxies comes from observations of the carbon monoxide (CO) lines (Bolatto et al. 2013; Carilli & Walter 2013). The notion that the neutral carbon line ($[\text{C}\,\text{I}]$) traces the bulk of the molecular gas mass has been investigated for more than four decades now (Phillips & Huggins 1981; Papadopoulos et al. 2004; Jiao et al. 2017; Valentino et al. 2018). On the other hand, in UV-intense and metal-poor environments, the use of $[\text{C}\,\text{I}]$ as a molecular gas tracer is limited due to the increased ionization of carbon. The limited usefulness of $[\text{C}\,\text{I}]$ has also been shown in dense conditions, i.e., in the collisional fronts of mergers (Michiyama et al. 2021). Bisbas et al. (2017) showed, however, that even if $[\text{C}\,\text{I}]$ is limited in such cases, it is still a more reliable tracer of global molecular mass than CO. This is due to the high sensitivity of the $[\text{C}/\text{CO}]$ abundance to even small changes in the cosmic-ray ionization rate, especially when the average gas densities are low ($<10^2 \text{ cm}^{-3}$). It is in such densities that the bulk of the H$_2$ reservoirs in galaxies is often found.
Recent episodes of star formation in galaxies can be pinpointed by the existence of gamma-ray bursts (GRBs) that are explosions of short-lived massive stars (Hjorth et al. 2003; Stanek et al. 2003). In this paper we take advantage of this feature to study the evolution of galaxies on the SFR–$M_*$ plane and its connection to the gas content by analyzing high-sensitivity observations of [C I] line emission toward selected GRB hosts. In particular, we want to shed light on the cause of weak [C I] lines of galaxies, i.e., if they are due to gas properties (e.g., density) or due to true low molecular gas content.

This paper is organized as follows. In Section 2 we describe the sample selection, observations, and reduction process. We also define the comparison sample from the literature and describe the methods used to derive fluxes, luminosities, and molecular masses. In Section 3 we describe the results of our analysis. Section 4 discusses our interpretation of the observables together with alternative scenarios. Finally, in Section 5 we present the conclusions of our work. Throughout this paper we use a cosmological model with $H_0 = 70 \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}$, $\Omega = 0.7$, and $\Omega_m = 0.3$.

2. Data

2.1. Sample Selection

The GRB host sample observed in [C I]$(3P_1−3P_0)$ (hereafter [C I]) was selected based on the availability of infrared or radio detections (Hunt et al. 2014; Michalowski et al. 2015; Perley et al. 2015), allowing precise estimates of SFRs. We selected hosts with spectroscopic redshifts so that their [C I] lines were expected to be observed away from atmospheric water lines. This resulted in seven potential targets (the hosts of GRB 051006, 051022, 060814, 061121, 080207 100316D, and 111005A). Depending on their declinations, these sources were observed with the Atacama Pathfinder Experiment (APEX) or the Institute for Radio Astronomy in the Millimeter Range (IRAM) 30 m radio telescope. The hosts of GRB 111005A, 051006, and 051022 were not observed, because they are at the lower redshift range proposed for a given telescope, resulting in a high observing frequency at which the weather requirements were challenging.

Low-redshift targets (GRB 061121 and 100316D) were only suitable for the APEX telescope because for them the observing frequency is high and requires very stable weather conditions and also a very low amount of precipitable water vapor. These stringent conditions are often attained at Chajnantor (the APEX site), but not at Pico Veleta (the IRAM 30 m telescope site).

2.2. Observations and Data Reduction

We observed the hosts of GRB 060814 and 080207 with the IRAM 30 m telescope (proposal 172-16; PI: M.J.M.), equipped with the Eight Mixer Receiver (Carter et al. 2012). We implemented the wobbler-switching mode and the Fourier transform spectrometer (FTS)-200 providing 195 kHz spectral resolution and 16 GHz bandwidth in each linear polarization. The observations for both targets were executed between 2017 February 1 and 2017 May 22 and lasted in total 13.1 hr on-source for GRB 060814 and 17.8 hr for GRB 080207. The observations were divided into 6 minute scans, each consisting of 12 subscans 30 s long. Pointing was checked and corrected every 1–2 hr. Each spectrum was calibrated and corrected for baseline shape. The spectra were aligned in frequency and noise-weight averaged. Some well-known platforming, due to the fact that the instantaneous bandwidth of 4 GHz is sampled by three different FTS units, was corrected offline by a dedicated procedure within the Continuum and Line Analysis Single Dish Software (CLASS). In all cases, the [C I] line is far away from the step of the platforming.

The hosts of GRB 061121 and 100316D were observed with the APEX telescope (Güsten et al. 2006; proposals 098.F-9300 and 098.D-0243; PI: M.J.M.), equipped with the Swedish Heterodyne Facility Instrument (SHExF; Belitsky et al. 2006; Vassilev et al. 2008). However the upper limits were not sufficiently constraining to allow robust conclusions about the molecular content of these sources; hence, we do not report the results for these galaxies.

All data were reduced and analyzed using the CLASS package within the Grenoble Image and Line Data Analysis Software: GILDAS. We took advantage of this package within the Grenoble Image and Line Data Analysis Software: GILDAS.

The obtained [C I] spectra of our two GRB (060814 and 080207) hosts are shown in Figure 1.

2.3. Comparison Sample

In order to place our two GRB hosts into a general perspective we compiled a sample of galaxies spanning several orders of magnitude in stellar mass, SFR, and gas mass. In particular, this compilation contains normal SFGs (Bourne et al. 2019; Valentino et al. 2020b; Dunne et al. 2021), (U) LIRGs (Lu et al. 2017; Valentino et al. 2020b; Michiyama et al. 2021), intermediate-$z$ isolated LIRGs (Lee et al. 2017) and merging starburst ULIRGs (Combes et al. 2011), high-$z$ starbursts (Shi et al. 2018), and transitioning isolated and merging galaxies (Cheng et al. 2018; Hogan et al. 2022). For all sources with [C I] data, $M_{\text{mol}}$ has been estimated here in a consistent manner (see Section 2.4). We used the total far-infrared luminosity to estimate the SFR (Kennicutt 1998) as

$$\text{SFR} = L_{\text{IR}}/(9.86 \times 10^4) M_\odot \, \text{yr}^{-1}$$

(converted to the Chabrier 2003 initial mass function) and the fundamental plane (Lara-López et al. 2010) to estimate the oxygen metallicity (Valentino et al. 2018; Bourne et al. 2019; Dunne et al. 2021), for galaxies without these estimates in the literature. The latter is needed to estimate the metallicity-dependent conversion factor $\alpha_{\text{C I}}$ introduced below.

2.4. Flux, Luminosity, and Mass Measurements

Our deep observations of [C I] in GRB hosts show a lack of significant emission. We estimated 2σ upper limits of the line flux, luminosity, and molecular gas masses by integration within a velocity range of $−100$ to $100 \, \text{km} \, \text{s}^{-1}$ around the expected velocity of the [C I] line at the redshift of each source. For our sample, as well as for the data from other works, we estimated the [C I] luminosity $L_{\text{C I}}$, using the same prescription—Equation (3) in Solomon et al. (1997).

We employed two methods to estimate the molecular gas mass from the luminosity of the [C I] line. The first method is based on a theoretical analysis of the [C I] emission from the interstellar medium (ISM) assuming local thermal equilibrium given by Papadopoulos et al. (2004). Using their Equation (11),

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10 www.iram.es/IRAMES/mainWiki/EmirForAstronomers

11 www.iram.fr/IRAMFR/GILDAS
evaluating all the constants we derived an expression to estimate the molecular gas mass from the [C I](1–0) line flux as

\[
\frac{M_{\text{mol}}}{M_{\odot}} = 1.3747 \times 10^{-9} \frac{D_L^2}{1 + z} \frac{I_{C1}}{X_{\text{C I}} A_{10} Q_{10}},
\]

where the abundance ratio is \(X_{\text{C I}} = 3 \times 10^{-5}\) (Jiao et al. 2017; Valentino et al. 2018), the Einstein coefficient for this transition is \(A_{10} = 7.93 \times 10^{-8}\) s\(^{-1}\), \(Q_{10}\) is given by Equation (A15) from Papadopoulos et al. (2004) with assumed \(T_{\text{kin}} = 40\) K, \(D_L\) is the luminosity distance given in Mpc, and \(I_{C1}\) is the velocity-integrated [C I] line flux in units of Jy km s\(^{-1}\). We refer to this method as P04 (see Weiß et al. 2003 for a similar method). The second method is taken from Heintz and Watson (2020) and is based on the conversion factor \(\alpha_{\text{[C I]}}\) between \(M_{\text{mol}}\) and \(L_{C1}^\prime\), estimated from observations of the [C I] absorption line in spectra of GRB afterglows and quasi-stellar objects. In this case \(\alpha_{\text{[C I]}}\) is metallicity dependent. We refer to this method as H20.

<table>
<thead>
<tr>
<th>GRB</th>
<th>(I_{C1})</th>
<th>(\log(L_{C1}))</th>
<th>(\log(M_{\text{mol}}/M_{\odot}))</th>
<th>P04</th>
<th>H20</th>
<th>M18</th>
</tr>
</thead>
<tbody>
<tr>
<td>060814</td>
<td>0.064±0.113</td>
<td>9.178</td>
<td>9.852</td>
<td>10.859</td>
<td>10.92</td>
<td></td>
</tr>
<tr>
<td>080207</td>
<td>0.016±0.139</td>
<td>9.504</td>
<td>10.17</td>
<td>10.777</td>
<td>11.3</td>
<td></td>
</tr>
</tbody>
</table>

**Notes.** The [C I] fluxes are given with their 2σ errors, while luminosities and molecular masses are 2σ upper limits. The errors were obtained by randomly perturbing 1000 times the fluxes of each channel in the spectra within their errors and assessing the 95% confidence interval of the obtained integrated fluxes. The measurements of \(M_{\text{mol}}\) for all the methods include the \(\mu = 1.36\) factor accounting for the contribution from helium and heavier elements. The last column (M18) reports CO-based molecular mass from Michalowski et al. (2018).

* Molecular masses from this work using methods P04 and H20.

3. Results

All of the measurements obtained for our GRB hosts are given in Table 1. The upper limits are 2σ. The SFRs, stellar masses, and spectroscopic redshifts from the literature are given in Table 2.

<table>
<thead>
<tr>
<th>GRB</th>
<th>(z)</th>
<th>SFR ((M_{\odot} \text{ yr}^{-1}))</th>
<th>(\log(M_*/M_{\odot}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>060814</td>
<td>1.92 (H12)</td>
<td>256.0 (P15)</td>
<td>10.2 (P15)</td>
</tr>
<tr>
<td>080207</td>
<td>2.09 (H12)</td>
<td>170.0 (H12)</td>
<td>11.17 (H14)</td>
</tr>
</tbody>
</table>

**Note.** References in parentheses are H12: Hjorth et al. (2012); H14: Hunt et al. (2014); P15: Perley et al. (2015).

Note that in both methods a factor \(\mu = 1.36\) that corrects for the contribution from helium and heavier elements is included.

#### 3.1. [C I] Luminosity

In Figure 2 we show the SFRs as a function of [C I] line luminosity \(L_{C1}^\prime\) [K km s\(^{-1}\) pc\(^{-2}\)] for our sample and for data from the literature for which the [C I] fluxes were available (Lu et al. 2017; Bourne et al. 2019; Valentino et al. 2020b; Dunne et al. 2021; Michiyama et al. 2021). Using only data for SFG from the literature (gray empty markers), we find the best-fit relation between \(L_{C1}^\prime\) and SFR as

\[
\log(\text{SFR}[M_{\odot} \text{ yr}^{-1}]) = 0.952 \times \log(L_{C1}^\prime) - 7.165,
\]

which holds over a wide redshift range (0 \(< z < 3\)) with 2σ scatter of 0.27 dex. As shown in Figure 2, the hosts of GRBs 060814 and 080207 have lower \(L_{C1}^\prime\) (by >0.8 and >0.3 dex, respectively) than expected for their SFRs based on our best fit. It has been shown for GRB hosts, in general, that, we can rule out the possible contamination of the emission by active
galactic nuclei at the wavelengths used to estimate SFRs (Perley et al. 2015), so we consider these SFRs to be robust.

In Figure 2 we also show the local (U)LIRG merging galaxies (Michiyama et al. 2021), which together with our low-$L_{\text{C}1}$ GRB hosts are found above the SFG population in terms of their SFR. This is also clearly visible in the right panel of the figure where the scatter around the best-fit relation is shown. In particular, the red cross symbol shows NGC 7679, the [C I]-dark AGN host found by Michiyama et al. (2021). The [C I]/CO ratio of 0.07 of this galaxy is below those of other ULIRGs (Jiao et al. 2017). Using the CO data from Michalowski et al. (2018) we estimated the [C I]/CO ratio of our GRB hosts to be of the order of $<0.1$. This is lower than normal ULIRGs but not as low as [C I]-dark galaxies like NGC 7679 or NGC 6052 studied in Michiyama et al. (2020) and Michiyama et al. (2021). On average (U)LIRGs have 0.6 dex lower $L_{\text{C}1}$, while the [C I]-dark NGC 7679 has 1.2 dex lower $L_{\text{C}1}$ than the expectations from the $L_{\text{C}1}$–SFR fit.

3.2. Molecular Gas Mass

In Figure 3 we show the estimated molecular gas masses of our GRB hosts based on $L_{\text{C}1}'$, using our two different methods (see Section 2.4 for details). We include the same data as in Figure 2, together with local LIRG NGC 1674 (König et al. 2013), intermediate-$z$ isolated LIRGs (Lee et al. 2017), intermediate-$z$ merging starburst ULIRGs (Combes et al. 2011), high-$z$ starburst ULIRGs (Shi et al. 2018), and low- and intermediate-$z$ transitioning isolated and merging galaxies (Cheng et al. 2018; Hogan et al. 2022) with the molecular mass estimated from CO emission (i.e., these have the same $M_{\text{mol}}$ in both panels, and are shown for comparison only). Using the SFG sample from the literature (gray open markers) we find the best-fit relation between SFR and [C I]-based $M_{\text{mol}}$ for each of the methods. The results of the fitting are given in each panel. The $M_{\text{mol}}$ for the GRB 060814 and 080207 host galaxies are found to be lower by >0.8 and >0.2 dex from our best fit for the P04 method. At least in the case of the host galaxy of GRB 060814 the offset is in agreement with the distance from the best-fit estimated for (U)LIRGs ($\sim0.8$ dex), high-$z$ starburst ($\sim0.7$), NGC 1674 ($\sim0.9$ dex), and the transitioning SFG mergers ($\sim0.4$ dex).

The range of the molecular gas mass in isolated SFGs (blue markers), merging transitioning systems (magenta), and starbursts (black) is similar (between $10^{8.5}$ and $10^{11}M_{\odot}$), but their SFRs vary significantly from tens to thousands solar masses per year, which translates to different depletion times (or SFES; see Section 3.3). Considering the second method used (H20), which is metallicity dependent, we can see that the majority of the ULIRGs, including our GRB hosts, have $M_{\text{mol}}$ above, but within the scatter of, the best-fit relation.

3.3. Main Sequence and Depletion Times

To establish whether the position of GRB hosts in Figures 2 and 3 is due to low $L_{\text{C}1}'$ or elevated SFRs, we investigate their location relative to the MS. Figure 4 shows the stellar mass as a function of SFR and the MS for SFGs at different redshifts (Speagle et al. 2014). While intermediate-$z$ LIRGs are found on their MS, the GRB hosts, (U)LIRGs, and transitioning SFGs are found to lie above the MS for their redshifts. To better quantify this, the distance from the MS is estimated as the ratio of the observed SFR to the SFR of a galaxy on the MS with the same stellar mass and redshift ($\text{SFR}/\text{SFR}_{\text{MS}}$).

In the right panel of Figure 4, we show the molecular gas depletion timescale ($M_{\text{mol}}$/SFR using the P04 method, or CO-based molecular gas masses from the literature when necessary), as a function of the distance to the MS. We find that GRB 060814 is about 7 times above the MS, while GRB 080207 lies on the corresponding MS within the scatter. The intermediate-$z$ isolated LIRGs lie close to the MS, while isolated transitioning galaxies are found 1 order of magnitude above it. The transitioning merging galaxies and starburst merging ULIRGs are found at even greater distances (with an average offset of a factor of 20 and 77, respectively).

We obtained relatively short gas depletion times of $<64$ and $<238$ Myr ($2\sigma$ upper limits) for the hosts of GRBs 060814 and 080207, respectively. These values are similar to those of high-$z$ starbursts for which we obtain a mean depletion time of 84 Myr and of transitioning mergers with an average of 205 Myr. The shortest depletion times (15 Myr on average) are found in intermediate-$z$ merging ULIRGs galaxies. As expected, the isolated LIRGs and isolated transitioning galaxies show longer depletion times of $\sim$1 Gyr on average.

In the right panel of Figure 4 we can see that with the gradual departure from the MS, the depletion time decreases. Gao & Solomon (2004b) showed that the fraction of the dense gas is the primary predictor of the SFR and that the relation between these quantities is similar for different galaxy types. Here we can see that the merging process plays an important role in decreasing depletion time (or increasing SFE). Indeed, for the dense environment, it has been shown that the gas is converted...
quicker to stars, in particular in gas-rich mergers (Genzel et al. 2010). Perhaps this is to be expected given that in mergers there are much more turbulent molecular gas reservoirs, whose higher Mach numbers will place more gas at high densities ($\geq 10^5$ cm$^{-3}$).

### 4. Discussion

A common feature for both GRB hosts studied in this work is a sensitive [C I] nondetection implying relatively low [C I] emission. The disturbed multicomponent morphology in the Hubble Space Telescope imaging of both galaxies suggests an ongoing merger process (Svensson et al. 2012; Blanchard & Berger 2016; Chrimes et al. 2019; Schneider et al. 2022). In what follows we put forward two nonexclusive scenarios to explain this feature. The first one is that the GRB hosts are caught at their transition from the main sequence toward the starburst phase (Cheng et al. 2018; Michiyama et al. 2021; Hogan et al. 2022). The second possibility is that they are [C I]-dark galaxies, which may explain their low [C I]/CO brightness temperature ratio (Jiao et al. 2017; Michiyama et al. 2020).

#### 4.1. Transition to Starburst

Our GRB hosts exhibit lower molecular masses than the best fit to normal galaxies (Figure 3), similar to merging ULIRGs and high-\(z\) starbursts. Moderate SFRs (as for the redshift of our GRB hosts) result in distances from their MS in between what measured for intermediate-\(z\) isolated LIRGs and that for intermediate- and high-\(z\) starbursts. Estimated depletion times ($M_{\text{mol}}/\text{SFR}$) are similar to those of transitioning merger galaxies, while being shorter than intermediate-\(z\) isolated LIRGs, and isolated transitioning galaxies, and longer (by about 1 order of magnitude) than the merging intermediate- and high-\(z\) starburst galaxies (Figure 4, right panel). The moderate distances from the MS and short depletion times suggest that our GRB hosts are observed in their transition toward the starburst phase. Given the morphology, this increase in SFR is likely caused by mergers. The existence of GRB events indicates that this may be the beginning of such a transition, because the progenitors of GRBs are short-lived stars.

We note that estimated depletion times assume no feedback effects (e.g., energetic winds from massive stars, radiative pressure). These effects have been found to be a possible cause of the enlargement of the time over which starburst galaxies consume their available cold gas reservoirs. In this work we treat all the galaxies in the same manner, i.e., depletion times are estimated without such feedback effects (Semenov et al. 2017; Díaz-García & Knapen 2020); thus, we consider this comparison as valid. Moreover, the depletion times are not used to draw any conclusions about the timescale of running out of gas.

#### 4.2. [C I]-dark Galaxies

The [C I] nondetection may be caused by an underabundance of carbon, rather than low molecular hydrogen mass. This
would result in a [C I]-dark object. The [C I]-dark galaxies are characterized by a low [C I]/CO temperature brightness ratio, below 0.1 (Michiyama et al. 2020; Michiyama et al. 2021), while regular ULIRGs have this ratio not lower than 0.2 (Jiao et al. 2017). These [C I]-dark galaxies have high hydrogen densities between $10^5$ and $10^6$ cm$^{-3}$, as shown using photo-dissociation region (PDR) models (Valentino et al. 2020b; Michiyama et al. 2020; Michiyama et al. 2021).

In standard models of PDRs, CO molecules are efficiently shielded from ultraviolet radiation at the dust extinction $A_V$ above a few mag, which could lead to low abundances of [C I] (Tielens & Hollenbach 1985). Recent models show, however, that the abundance ratio of [C I] over CO is linked more strongly with the cosmic-ray ionization rate rather than the UV radiation field (Bisbas et al. 2017). Nevertheless, [C I] can be considered as a good tracer of H$_2$ gas in mergers, except in the highest-density medium where carbon is locked in CO. Such high densities are indeed commonly detected toward [C I]-dark objects that have undergone a merger event (Michiyama et al. 2020; Michiyama et al. 2021).

The proposed explanations of transitioning-to-starburst galaxies and [C I]-dark galaxies may be related. The low [C I]/CO line ratio in [C I]-dark galaxies could be an effect of mergers yielding high average density H$_2$ gas reservoirs but with a yet-to-be-fully-ignited starburst, producing lower average cosmic-ray energy densities. The combination of high $n_{H_2}$ and low cosmic-ray energy density can then naturally produce [C I]-dark galaxies, albeit only for short cosmic time intervals. In that regard, it would be interesting to examine whether [C I]-dark galaxies of this type deviate from the far-infrared–radio correlation, i.e., with lower synchrotron emission for a given far-infrared luminosity. The estimated upper-limit [C I]/CO temperature brightness ratio of <0.1 for the GRB 080207 hosts places it in the regime of [C I]-dark galaxies. Very high gas density between $10^5$ and $10^6$ cm$^{-3}$ has also been inferred for this galaxy using a [C II] marginal detection (Hashimoto et al. 2019), which is consistent with the proposed [C I]-dark nature of the host. Both our GRB hosts also have low [C I] luminosities for their SFRs. In the case of the GRB 060814 host, the [C I] and CO were not detected, so we cannot confirm or rule out this interpretation for this galaxy. High gas densities were also claimed for other GRB hosts (Christensen et al. 2008; Michalowski et al. 2014; Arabsalmani et al. 2015; Michalowski et al. 2015, 2016; Arabsalmani et al. 2019, 2020; de Ugarte Postigo et al. 2020; Arabsalmani et al. 2022).

Thus, until additional observations (e.g., of HCN to trace the dense gas phase) are available we conclude that both GRB hosts are candidates for [C I]-dark galaxies that are transitioning toward the starburst phase with the merger event being the cause.

### 4.3. Ruled-out Mechanism: Poststarbursts

In principle, our galaxies might be observed in the poststarburst phase, on the way down from the starburst regime. This would explain their SFRs and low gas content. However, this possibility is inconsistent with the presence of optical emission lines, indicating recent star formation. Furthermore, Balmer absorption features are not detected in the spectra of these GRB hosts (Krühler et al. 2015), unlike for poststarburst galaxies. Poststarburst galaxies have low SFRs and high metallicities, so while it is not impossible (e.g., Rossi et al. 2014; Levan et al. 2023), they are less likely to host a GRB, as opposed to an early starburst phase.

### 5. Conclusions

Our targets display spectra indicative of a young stellar population and have slightly increased SFRs relative to their MS (Perley et al. 2013; Krühler et al. 2015). Based on our [C I] emission line measurements, we have inferred a molecular gas content similar to that of local ULIRGs but lower than would be expected from the best fit to the normal star-forming galaxies (see Figures 2 and 3). We propose that these are high-$z$ merger systems caught at the transition from the main sequence toward the starburst phase. These are high-redshift analogs to
the intermediate-$z$ transitioning galaxies (Cheng et al. 2018; Hogan et al. 2022). Furthermore, their low [C I]/CO ratios point to a high-density environment observed in the collisional fronts of mergers (Valentino et al. 2020b; Michiyama et al. 2020; Michiyama et al. 2021). Indeed, the merger signatures have been observed for our GRB hosts (Svensson et al. 2012; Blanchard et al. & Berger 2016; Chrimes et al. 2019; Schneider et al. 2022). While such merger-driven starbursts play a lesser role in the overall star formation rate density at $z = 2$ (Rodighiero et al. 2011), these systems may play a crucial role in the quenching and morphological transformation.

To test whether these galaxies indeed contain dense molecular star-forming clouds it would be essential to observe their emission of the high dipole-moment molecule HCN (Gao & Solomon 2004a). This, however, will be challenging because of the weakness of the HCN line. Additionally, the deep, high-resolution imaging of [C I] and CO (e.g., with the NOEMA interferometer) would be helpful to study the relative location of [C I] and CO, which again is not an easy task considering that both GRB hosts are at $z \sim 2$.

Acknowledgments

We thank the anonymous reviewer for all the comments that helped to improve our work. J.N., M.J.M., M.S., and A.L. acknowledge the support of the National Science Centre, Poland through the SONATA BIS grant 2018/30/E/ST9/00208. This research was funded in whole or in part by National Science Centre, Poland (grant number: 2021/41/N/ST9/02662). J.R.R. acknowledges support by grant PID2019-105552RB-C41 funded by MCIN/AEI/10.13039/501100011033. A.K. acknowledges support from the First TEAM grant of the Foundation for Polish Science No. POIR.04.04.00-00-5D21/18-00 and the Polish National Agency for Academic Exchange grant No. BPN/BEK/2021/1/00319/DEC/1. This article has been supported by the Polish National Agency for Academic Exchange under grant No. PPI/APM/2018/1/00036/U/001. A.R. acknowledges support from the INAF project Premiale Supporto Italia & Arlita. J.H. was supported by a VILLUM FONDEN Investigator grant (project number 172-16) with the Swedish observations on APEX are supported through Swedish participation in GHOSTS database 

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Facilities: APEX (Güsten et al. 2006), IRAM 30 m (Carter et al. 2012).
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