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THE OPTICALLY UNBIASED GRB HOST (TOUGH) SURVEY. VI. RADIO OBSERVATIONS AT $z \lesssim 1$ AND CONSISTENCY WITH TYPICAL STAR-FORMING GALAXIES*

M. J. Michałowski[1,2], A. Kamble[3], J. Hjorth[2], D. Malesani[2], R. F. Reinfrank[4,5], L. Bonavera[6], J. M. Castro Cerón[7], E. Ibar[8], J. S. Dunlop[1], J. P. U. Fynbo[2], M. A. Garrett[9,10,11], P. Jakobsson[12], D. L. Kaplan[3], T. Krühler[2], A. J. Levan[13], M. Massardi[14], S. Pal[15], J. Sollerman[16], N. R. Tanvir[17], A. J. van der Horst[18], D. Watson[2], and K. Wiersema[17]

[1] SUPA (Scottish Universities Physics Alliance), Institute for Astronomy, University of Edinburgh, Royal Observatory, Edinburgh EH9 3HJ, UK; mm@roe.ac.uk
[2] Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, DK-2100 Copenhagen Ø, Denmark
[3] Physics Department, University of Wisconsin-Milwaukee, Milwaukee, WI 53211, USA
[4] CSIRO Astronomy and Space Science, P.O. Box 76, Epping, NSW 1710, Australia
[5] School of Chemistry and Physics, The University of Adelaide, Adelaide, SA 5005, Australia
[6] Instituto de Física de Cantabria, CSIC-Universidad de Cantabria, Avda. de los Castros s/n, E-39005 Santander, Spain
[7] Department of Radio Astronomy, Madrid Deep Space Communications Complex (INTA-NASA/INSA), Ctra. M-531, km. 7, E-28.294 Robledo de Chavela (Madrid), Spain
[8] UK Astronomy Technology Centre, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK
[9] Netherlands Institute for Radio Astronomy (ASTRON), Postbus 2, 7990 AA Dwingeloo, The Netherlands
[10] Leiden Observatory, University of Leiden, P.B. 9513, Leiden 2300 RA, The Netherlands
[11] Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Hawthorn, Victoria 3122, Australia
[12] Centre for Astrophysics and Cosmology, Science Institute, University of Iceland, Dunhagi 5, 107 Reykjavík, Iceland
[13] Department of Physics, University of Warwick, Coventry CV4 7AL, UK
[14] INAF-Istituto di Radioastronomia, via Gobetti 101, I-40129 Bologna, Italy
[15] ICRAR, University of Western Australia, 35 Stirling Highway, Crawley, WA, Australia
[16] The Oskar Klein Centre, Department of Astronomy, AlbaNova, Stockholm University, SE-10691 Stockholm, Sweden
[17] Department of Physics and Astronomy, University of Leicester, University Road, Leicester LE1 7RH, UK
[18] Astronomical Institute "Anton Pannekoek," University of Amsterdam, Science Park 904, 1098XH Amsterdam, The Netherlands
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ABSTRACT

The objective of this paper is to determine the level of obscured star formation activity and dust attenuation in a sample of gamma-ray burst (GRB) hosts, and to test the hypothesis that GRB hosts have properties consistent with those of the general star-forming galaxy populations. We present a radio continuum survey of all $z < 1$ GRB hosts in The Optically Unbiased GRB Host (TOUGH) sample supplemented with radio data for all (mostly pre-*Swift*) GRB-SN hosts discovered before 2006 October. We present new radio data for 22 objects and have obtained a detection for three of them (GRB 980425, 021211, 031203; none in the TOUGH sample), increasing the number of radio-detected GRB hosts from two to five. The star formation rate (SFR) for the GRB 021211 host of $\sim 825\,M_\odot$ yr^{-1}, the highest ever reported for a GRB host, places it in the category of ultraluminous infrared galaxies. We found that at least ∼63% of GRB hosts have SFR $< 100\,M_\odot$ yr^{-1} and at most ∼8% can have SFR $> 500\,M_\odot$ yr^{-1}. For the undetected hosts the mean radio flux ($<35\,\mu$Jy 3σ) corresponds to an average SFR $< 15\,M_\odot$ yr^{-1}. Moreover, $\gtrsim$88% of the $z \lesssim 1$ GRB hosts have ultraviolet dust attenuation $A_{\rm UV} < 6.7$ mag (visual attenuation $A_V < 3$ mag). Hence, we did not find evidence for large dust obscuration in a majority of GRB hosts. Finally, we found that the distributions of SFRs and $A_{\rm UV}$ of GRB hosts are consistent with those of Lyman break galaxies, Hα emitters at similar redshifts, and of galaxies from cosmological simulations. The similarity of the GRB population with other star-forming galaxies is consistent with the hypothesis that GRBs, a least at $z \lesssim 1$, trace a large fraction of all star formation, and are therefore less biased indicators than once thought.

Key words: dust, extinction – galaxies: evolution – galaxies: ISM – galaxies: star formation – gamma-ray burst: general – radio continuum: galaxies

Online-only material: color figures

1. INTRODUCTION

Long gamma-ray bursts (GRBs) mark the endpoint of the lives of very massive stars (e.g., Hjorth et al. 2003; Stanek et al. 2003) and due to the short lifetimes of such stars, they are believed to be excellent tracers of ongoing star formation in distant galaxies (Jakobsson et al. 2005; Yüksel et al. 2008; Kistler et al. 2009; Butler et al. 2010; Elliott et al. 2012; Robertson & Ellis 2012). However, before GRBs can be quantitatively used to trace the star formation history of the universe, the properties of their host galaxies and the biases of the GRB samples must be understood.

From optical/near-infrared studies we know that GRB hosts are often faint dwarf galaxies (Le Floc'h et al. 2003; Christensen et al. 2004; Savaglio et al. 2009; Castro Cerón et al. 2010; Levesque et al. 2010b; Svensson et al. 2010). However, some host galaxies of (often optically obscured) GRBs are massive ($M_* \gtrsim 10^{10.5}\,M_\odot$) and/or belong to the category of luminous infrared galaxies (LIRGs; $L_{\rm IR} > 10^{11}\,L_\odot$; or star formation rate (SFR) $\gtrsim 17.2\,M_\odot$ yr^{-1} using the conversion of Kennicutt 1998), e.g., GRB 980613 (Castro Cerón et al. 2006, 2010), 020127 (Berger et al. 2007), 020819B (Savaglio et al. 2009; Küpcü Yoldaş et al. 2010), 051022 (Castro-Tirado et al. 2007; Savaglio et al. 2009), 070306 (Jaunsen et al. 2008; Krühler et al.

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2011), 080207 (Hunt et al. 2011; Svensson et al. 2012), 080325 (Hashimoto et al. 2010), and 080605 (Krühler et al. 2012a). Hence, the diversity of the GRB host sample is not yet fully described.

Moreover, short-wavelength emission does not give us a complete picture of GRB hosts, as it misses star formation that is heavily obscured by dust. Unfortunately, long-wavelength emission has been detected only in a handful of GRB hosts (Berger et al. 2001, 2003a; Frail et al. 2002; Tanvir et al. 2004; Castro Cerón et al. 2006; Le Floc'h et al. 2006, 2012; Priddey et al. 2006; Michałowski et al. 2009; Stanway et al. 2010; Hunt et al. 2011; Watson et al. 2011; Hatsukade et al. 2012; Svensson et al. 2012; Walter et al. 2012; see the compilation of submillimeter observations in de Ugarte Postigo et al. 2012), which hampers our ability to study GRB hosts in the context of galaxy evolution, as a significant fraction of star formation in the universe is believed to be obscured by dust (e.g., Le Floc'h et al. 2005; Chapman et al. 2005; Wall et al. 2008; Michałowski et al. 2010a).

Here, we attempt to improve this situation through an extensive multi-facility radio survey of GRB hosts limited to $z < 1$ to obtain meaningful SFR limits, drawn from The Optically Unbiased GRB Host (TOUGH; Hjorth et al. 2012) survey, which allows for unbiased statistical analysis.

Observations at radio wavelengths provide an unobscured (unaffected by dust) view on star-forming galaxies by directly tracking the recent ($\lesssim$100 Myr) star formation activity through synchrotron radiation emitted by relativistic electrons accelerated by supernova (SN) remnants (Condon 1992). Moreover, even though the radio emission accounts for only a fraction of the bolometric luminosity of a galaxy, it is well correlated with the infrared emission, a good tracer of both the SFR and the dust mass in a galaxy. Finally, the timescale probed by radio emission ($\lesssim$100 Myr) is much longer than the lifetime of a GRB progenitor ($\sim$5–8 Myr; Sollerman et al. 2005; Hammer et al. 2006; Östlin et al. 2008; Thöne et al. 2008), so the radio emission probes the average star formation state of a galaxy, unlike a GRB rate, which measures the almost instantaneous star formation activity.

The objective of this paper is to (1) determine the level of obscured star formation activity and dust attenuation in a representative sample of $z \lesssim 1$ GRB hosts, and (2) test the hypothesis that GRB hosts are consistent with the general star-forming galaxy populations at similar redshifts.

We use a cosmological model with $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_\Lambda = 0.7$, and $\Omega_{\rm m} = 0.3$ and assume the Salpeter (1955) initial mass function to which all estimates from the literature were converted to, if necessary.

2. SAMPLE

Our target sample is composed of two subsets. The main subset is drawn from TOUGH sample based on the *Swift* satellite and a Very Large Telescope (VLT) Large Programme. The survey design, the selection criteria, and the summary of the host properties (including redshifts) are presented in Hjorth et al. (2012), the photometry and the host properties are analyzed in Malesani et al. (2012), the redshifts are presented in Jakobsson et al. (2012) and Krühler et al. (2012b), and the Lyα properties are discussed in Milvang-Jensen et al. (2012). The reduced data will be available from the TOUGH Web site.[19] The sample includes *all* long GRBs that exploded between 2005 March 1 and 2007 August 10, observable from the southern hemisphere ($-70° < \delta < +27°$), with low Galactic foreground extinction ($A_V \leqslant 0.5$ mag) and no bright star nearby, for which X-ray observations are available <12 hr after the burst (with $\leqslant 2''$ error circle radius) to allow the determination of accurate positions. Therefore, this X-ray-selected sample is constructed in a way that it is not biased against dusty systems and the selection does not depend on the host luminosity. We note that the availability of redshift does depend on the host luminosity, but redshifts were measured for $\sim$77% (53/69) of *Swift*/VLT TOUGH GRBs (Hjorth et al. 2012; Jakobsson et al. 2012). Moreover, half of the TOUGH GRB redshifts were obtained from optical observations of afterglows, so the redshift recovery fraction is dependent on the host brightness only for the other half. Finally, fainter hosts (for which redshifts could not be measured) are less likely to be at $z < 1$. Indeed, 75% (12/16) of TOUGH GRBs with unknown redshifts are fainter than $R = 25$ mag, whereas the same is true only for $\sim$17% (2/12) of GRBs confirmed to be at $z < 1$. We therefore conclude that the $z < 1$ TOUGH sample has a completeness nearing 100%, and, in any case, larger than $\sim$77%.

We restricted the TOUGH sample to $z < 1$ to obtain meaningful radio constraints on SFRs. The $z < 1$ TOUGH unbiased subset consists of 12 hosts, all of which were observed within our program (see Table 1 for observation logs). GRB 060814 at $z = 1.92$, 050915A at $z = 2.527$, and 070808 with currently no redshift measurement are in our target sample because they were initially believed to be at $z < 1$ (e.g., Thöne et al. 2007).

The second subset includes (mostly pre-*Swift*) GRBs that were spectroscopically or photometrically confirmed to be associated with SNe before 2006 October, namely, the sample of Ferrero et al. (2006) plus GRB 980425/SN 1998bw (Galama et al. 1998) and GRB 040924 (Soderberg et al. 2006). We targeted GRB-SN hosts because their progenitors are securely established to be connected with recent star formation (see Hjorth & Bloom 2011 for a recent review of the GRB-SN connection). Since the detection of an SN component in a fading GRB afterglow is difficult at high redshifts, this selection imposes a practical limit of $z \lesssim 1$. In total, 15 hosts were selected (with an overlap of two hosts with the TOUGH subset), eight of which were observed within our program and for the remaining seven the deep radio upper limits from the literature were adopted (see Table 2).

In summary, our sample consists of 30 GRB hosts and we provide new radio observations for 22 of them.

3. DATA

The radio data were collected using the Australian Telescope Compact Array (ATCA; proposals C1651, C1741, CX228) in the 6 km configuration (H168 for GRB 980425), the Giant Metrewave Radio Telescope (GMRT; proposals 12MMc01, 13MMc01, 16_093), the Very Large Array (VLA; proposal AM902) in A configuration, and the Westerbork Synthesis Radio Telescope (WSRT; proposals R07B004, R08A002) in maxi-short configuration. The log of observations is presented in Table 1.

Data reduction and analysis were done using the MIRIAD (Sault & Killeen 2004) and AIPS[20] packages. Calibrated visibilities were Fourier transformed using "robust" or "uniform"

[19] http://www.dark-cosmology.dk/TOUGH

[20] http://www.aips.nrao.edu/cook.html

Table 1
Radio Observation Logs

GRB	Array	Observation Dates	t [a]	Frequency (hr)	rms (GHz)	Synth. Beam Size (μJy)	Calibrators[b] (″)
			GRB-SN subset				
980425[c,d]	ATCA	2007 Aug 18	9.00	4.8, 8.64	46, 27	76 × 38, 37 × 21	PKS B1934-638
991208	WSRT	2007 Aug 2–3	11.97	1.43	47	14.5 × 10.5	3C286, 3C48
020903	GMRT	2008 Jan 18–19, Mar 1	16.99	1.43	41	4.0 × 2.0	3C48, 2243-257
021211	VLA	2007 Jul 14	5.45	1.43	31	1.7 × 1.5	TXS 0542+498, PMN J0808+0514
031203[d,e]	ATCA	2008 Jan 26	6.97	1.39, 2.37	46, 37	8.5 × 3.4, 6.3 × 2.3	PKS B1934-638, PKS B0826-373
041006	GMRT	2007 Aug 7–8	9.61	1.43	181	7.3 × 2.0	3C48, B2 0026+34
			TOUGH $z < 1$ unbiased subset				
050416A	WSRT	2008 Apr 27–28	11.97	1.43	75	31.6 × 9.6	3C48, 3C286
050525A	WSRT	2007 Aug 13–14	11.97	1.43	52	33.7 × 14.8	3C48, 3C286
050824	WSRT	2007 Dec 26–27	11.97	1.43	100	39.9 × 15.5	3C147, 3C286
051016B	WSRT	2007 Dec 28–29	11.97	1.43	47	59.7 × 14.1	3C147, 3C286
051117B[d]	ATCA	2009 Aug 12	8.29	5.5, 9.0	12, 19	6.4 × 1.7, 3.9 × 1.1	PKS B1934-638, PKS B0607-157
060218	WSRT	2007 Aug 16–17	11.96	1.43	117	51.9 × 15.2	3C48, 3C286
060614[d]	ATCA	2009 Aug 9–10	8.84	5.5, 9.0	11, 14	3.1 × 1.9, 1.7 × 1.0	PKS B1934-638
060729	ATCA	2008 Jan 26, 28	11.36	1.39	35	7.4 × 6.4	PKS B1934-638, PKS B0515-674
060912A[f]	GMRT	2009 Jun 1–2	10.00	1.43	...	...	3C48
061021	ATCA	2008 Apr 18	7.90	1.39	36	20.0 × 4.8	PKS B1934-638, PKS B0919-260
061110A[f]	WSRT	2007 Dec 29	12.00	1.43	...	...	3C147, 3C286
070318	ATCA	2008 Apr 19	9.74	1.39	47	7.2 × 4.2	PKS B1934-638, PKS B0405-385
			Other hosts				
050915A	ATCA	2008 Jan 25, 27	15.62	1.39	29	18.3 × 5.5	PKS B1934-638, PKS B0451-282
...[d]	ATCA	2011 Dec 19	9.78	5.5, 9.0	12, 15	5.9 × 2.1, 3.7 × 1.3	PKS B1934-638, PKS B0537-286
060505[d]	ATCA	2009 Aug 10–11	8.48	5.5, 9.0	17, 14	5.2 × 1.7, 3.4 × 1.1	PKS B1934-638, PKS B2155-152
...	GMRT	2008 Jan 20–21	5.89	1.43	58	3.6 × 2.3	3C48, 2243-257
060814	WSRT	2007 Dec 30	11.96	1.43	78	42.7 × 14.9	3C48, 3C286
070808	GMRT	2009 Jun 2–3	6.87	1.43	68	3.6 × 2.2	3C48, 0022+002

Notes. The horizontal lines divide the GRB-SN and the $z < 1$ TOUGH subsets (see Section 2) and the hosts which do not belong to any of these subsets. GRBs 050525A and 060218 belong to the first two subsets.
[a] On-source integration time.
[b] The first (second) object was used as a primary (secondary) calibrator. For WSRT the indicated objects were used as primary calibrators at the beginning and the end of the run.
[c] Data published in Michałowski et al. (2009).
[d] This object was observed simultaneously at two frequencies; see Table 2.
[e] Data published in Watson et al. (2011).
[f] Poor quality (interference and system malfunctions) of the data impedes the flux density measurement.

weighting depending on which gave a better result for a particular field. The resulting rms noise, beam sizes, and calibrators are listed in Table 1 and the radio contours overlaid on the optical images for detected hosts are presented in Figure 1. The data for the observations of GRB 060912A and 061110A were found to have been severely affected by radio frequency interference and system malfunctions. Therefore, we had to discard a significant fraction of the data and the remaining data were insufficient to create reasonable radio images of the fields.

Flux densities were measured by fitting two-dimensional Gaussian functions to the region around the host and the errors were determined from the local rms on the images. The hosts of GRBs 980425 and 031203 slightly overlap with radio objects ∼70″ south (see Michałowski et al. 2009) and ∼6″ northwest, respectively, so their flux densities were estimated by simultaneous fitting two Gaussian functions with their centroids, sizes, and orientations as free parameters. The lack of residuals left after the subtraction of these two Gaussians rules out a significant contamination of the nearby objects to the measured flux densities of the hosts.

4. RESULTS

Our photometry measurements are presented in Table 2. Of 20 targeted hosts, 3 (GRB 980425, 021211, 031203) were detected (not counting upper limits from the literature). Two out of these detections are in fact the first- and third-closest GRBs in our sample. None of the hosts in the TOUGH subset has been detected. Hence, this program (Michałowski et al. 2009; Watson et al. 2011; this paper) increases the number of the radio-detected GRB hosts from two (GRB 980703, Berger et al. 2001; GRB 000418, Berger et al. 2003a) to five. Recently the host of GRB 031203 has also been detected at 5.5 GHz by Stanway et al. (2010).

We assume that the entire flux is due to star formation and not active galactic nucleus (AGN) activity, which is a well-tested hypothesis for GRB hosts (see discussion in Michałowski et al. 2008; Watson et al. 2011).

The SFRs derived from our radio data as well as from the ultraviolet (UV) data are presented in Table 2 and are shown as a function of redshift on Figure 2. The radio SFRs (SFR_{radio}) were calculated from the empirical formula of Bell (2003;

Table 2
Radio Fluxes, Star Formation Rates and Dust Attenuations of GRB Hosts

GRB	z	Ref	Flux Density (μJy)	Frequency (GHz)	Ref	$\mathrm{SFR_{radio}}$[a] ($M_\odot$ yr^{-1})	$\mathrm{SFR_{UV}}$[b] ($M_\odot$ yr^{-1})	Ref[c]	A_V[d] (mag)
GRB-SN subset									
970228	0.695	1	<69	1.43	30	<72	0.60	42	<2.3
980425	0.0085	2	420 ± 50	4.80	‡,31	0.23 ± 0.02	0.39	42	~0
...	...	...	<180	8.64	‡,31	<0.17	0.39	42	~0
990712	0.4337	3, 4	<105	1.39	32	<36	1.28	43	<1.6
...	...	...	<36	5.50	33	<35	1.28	43	<1.6
...	...	...	<129	9.00	33	<180	1.28	43	<2.4
991208	0.7063	5	<32	1.43	‡	<35	0.83	43	<1.8
000911	1.058	6	<57	8.46	34	<608	1.40	42	<3.0
010921	0.451	7	<83	1.43	30	<32	1.60	42	<1.5
011121	0.36	8	<120	4.80	30	<68	1.83	44	<1.8
020405	0.691	9	<42	8.46	35	<165	3.70	42	<1.9
020903	0.251	10	<53	1.43	‡	<5.39	0.42	44	<1.3
021211	1.006	11	330 ± 31	1.43	‡	825 ± 77	0.72	42	3.4
...	...	...	<34	2.10	36	<114	0.72	42	<2.5
...	...	...	<45	8.46	37	<427	0.72	42	<3.1
030329	0.168	12	<420	1.40	38	<17	0.14	42	<2.4
031203	0.105	13	254 ± 46	1.39	‡,39	3.83 ± 0.69	4.30	42	~0
...	...	...	191 ± 37	2.37	‡,39	4.29 ± 0.83	4.30	42	~0
...	...	...	216 ± 50	5.50	33	9.13 ± 2.11	4.30	42	0.4
...	...	...	<48	9.00	33	<3.09	4.30	42	~0
040924	0.859	14	<63	4.90	45	<274	0.66[e]	‡,45	<2.9
041006	0.716	14	<45	2.10	36	<67	0.47	44	<2.4
...	...	...	<348	1.43	‡	<392	0.47	44	<3.3
...	...	...	<123	8.46	41	<525	0.47	44	<3.4
TOUGH $z < 1$ unbiased subset									
050416A	0.6528	15, 16	<447	1.43	‡	<405	0.89	44	<3.0
050525A	0.606	17	<228	1.43	‡	<174	0.64	42	<2.7
050824	0.828	18, 19	<111	1.43	‡	<175	1.37	46	<2.4
051016B	0.9364	20	<220	1.43	‡	<465	5.69	‡,47	<2.2
051117B	0.481	21	<36	5.50	‡	<44	2.72	‡,47	<1.4
...	...	...	<57	9.00	‡	<101	2.72	‡,47	<1.8
060218	0.0334	22	<447	1.43	‡	<1.00	0.05	42	<1.4
...	...	...	<117	5.50	33	<0.78	0.05	42	<1.3
...	...	...	<42	9.00	33	<0.48	0.05	42	<1.1
060614	0.125	23	<33	5.50	‡	<2.35	0.02	42	<2.4
...	...	...	<42	9.00	‡	<3.72	0.02	42	<2.6
060729	0.54	24	<105	1.39	‡	<60	0.13	48	<3.0
061021	0.3463	25	<108	1.39	‡	<22	0.03[e]	‡,21	<3.2
070318	0.836	26	<141	1.39	‡	<223	1.44	‡,49	<2.5
Other hosts									
050915A	2.527	21, 27	<59	1.39	‡	<1204	9.48	‡,49	<2.4
...	...	...	<44	5.50	‡	<2521	9.48	‡,49	<2.7
...	...	...	<37	9.00	‡	<3032	9.48	‡,49	<2.8
060505	0.0889	28	<37	5.50	‡	<1.50	1.90	42	~0
...	...	...	<52	9.00	‡	<2.53	1.90	42	<0.1
...	...	...	<63	1.43	‡	<1.05	1.90	42	~0
060814	1.92	21, 27, 29	<430	1.43	‡	<4823	31.20	‡,49	<2.5
070808	unknown	...	<156	1.43	‡	...	...	...	...

Notes. The horizontal lines divide the GRB-SN and the $z < 1$ TOUGH unbiased subsets (see Section 2) and the hosts which do not belong to any of these subsets. GRBs 050525A and 060218 belong to the first two subsets. For non-detected targets 3σ limits are reported.

[a] Assuming radio spectral index $\alpha = -0.75$ and applying the calibration of Bell (2003).

[b] From UV continuum unless noted otherwise. Not corrected for dust attenuation.

[c] The symbol ‡ indicates that we derived the SFR from fluxes reported in the reference using the calibration of Kennicutt (1998) or Savaglio et al. (2009).

[d] Visual extinction calculated from the ultraviolet extinction $A_{\rm UV} = 2.5\log(\mathrm{SFR_{radio}}/\mathrm{SFR_{UV}})$ assuming an SMC extinction curve, which gives $A_{\rm V} = A_{\rm UV}/2.2$.

[e] From the [O II] line.

References. (‡) This work; (1) Bloom et al. 2001; (2) Tinney et al. 1998; (3) Galama et al. 1999; (4) Hjorth et al. 2000; (5) Castro-Tirado et al. 2001; (6) Price et al. 2002a; (7) Price et al. 2002b; (8) Infante et al. 2001; (9) Price et al. 2003; (10) Soderberg et al. 2004; (11) Vreeswijk et al. 2006; (12) Hjorth et al. 2003; (13) Prochaska et al. 2004; (14) Soderberg et al. 2006; (15) Cenko et al. 2005; (16) Soderberg et al. 2007; (17) Foley et al. 2005; (18) Fynbo et al. 2005; (19) Sollerman et al. 2007; (20) Soderberg et al. 2005; (21) Jakobsson et al. 2012; (22) Pian et al. 2006; (23) Price et al. 2006; (24) Thöne et al. 2006; (25) Fynbo et al. 2009; (26) Jaunsen et al. 2007; (27) Krühler et al. 2012b; (28) Ofek et al. 2006; (29) Salvaterra et al. 2012; (30) Frail et al. 2003; (31) Michałowski et al. 2009; (32) Vreeswijk et al. 2001; (33) Stanway et al. 2010; (34) Berger et al. 2003a; (35) Berger et al. 2003b; (36) Hatsukade et al. 2012; (37) Fox et al. 2003; (38) van der Horst et al. 2005; (39) Watson et al. 2011; (40) Wiersema et al. 2008; (41) Soderberg & Frail 2004; (42) Castro Cerón et al. 2010; (43) Christensen et al. 2004; (44) Savaglio et al. 2009; (45) Svensson et al. 2010; (46) Ovaldsen et al. 2007; (47) Cano et al. 2011; (48) Malesani et al. 2012.

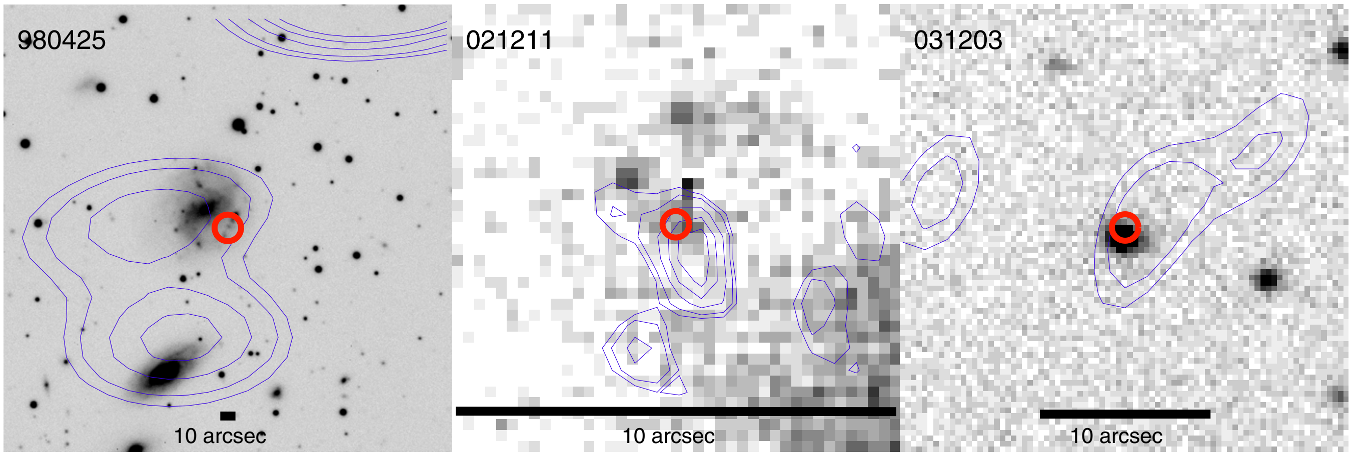

Figure 1. Radio contours (blue lines) overlaid on the optical images of the detected GRB hosts. The size of each image depends on the host galaxy size and the resolution of the radio data: 3′ for GRB 980425 (4.8 GHz), 10″ for GRB 021211 (1.43 GHz), and 20″ for GRB 031203 (1.39 GHz). The red circles (with arbitrary sizes) mark the position of GRBs (optical positions for GRB 980425 and 021211 from Fynbo et al. 2000; Fox et al. 2003; and X-ray position for GRB 031203 from Watson et al. 2004). The contours are 3σ, 4σ, 6σ, 8σ, and 10σ (see Table 1). North is up and east is left. The optical data are from Sollerman et al. (2005, GRB 980425), Della Valle et al. (2003, GRB 021211), and Mazzali et al. (2006, GRB 031203).

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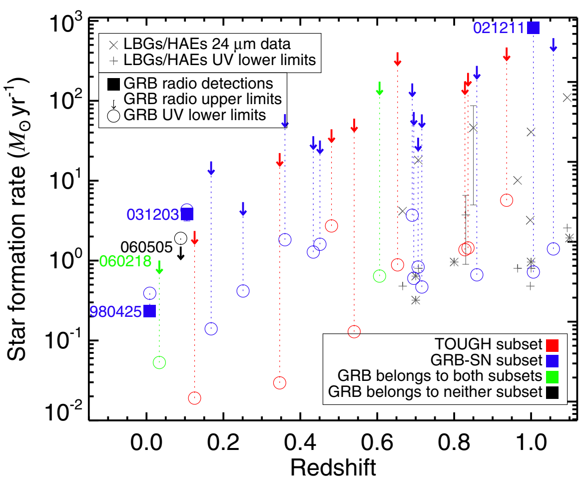

Figure 2. Star formation rates (SFRs) as a function of redshift of GRB host galaxies. Squares and arrows denote SFRs derived from radio detections and 3σ upper limits, respectively. Circles denote lower limits on SFRs derived from the ultraviolet (UV) data. For a given GRB, the radio and UV SFRs are connected by a dotted line. GRBs are color-coded depending on whether they belong to the $z < 1$ TOUGH unbiased subset (red symbols), the GRB-SN subset (blue symbols), both (green symbols), or none (black symbols). The right y-axis gives the corresponding infrared luminosity according to $\mathrm{SFR}(M_\odot\,\mathrm{yr}^{-1}) = 1.72 \times 10^{-10} L_{\mathrm{IR}}(L_\odot)$ (Kennicutt 1998). The three low-redshift hosts (GRB 980425, 031203, and 060505) are consistent with no dust attenuation as their $\mathrm{SFR}_{\mathrm{radio}}$ are similar to $\mathrm{SFR}_{\mathrm{UV}}$. On the other hand, huge dust attenuation must be invoked to explain a very high $\mathrm{SFR}_{\mathrm{radio}}$ of the host of GRB 021211. Crosses and plus symbols indicate the 24 μm and UV SFRs of Lyman break galaxies (LBGs; Basu-Zych et al. 2011) and Hα emitters (HAEs; mean values with standard deviations are shown; Sobral et al. 2009). GRB hosts are consistent with these populations.

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see Section 4.2 of Michałowski et al. 2009 for discussion of its applicability to GRB hosts) assuming a radio spectral index[21] $\alpha = -0.75$ (Condon 1992; Ibar et al. 2010). This choice of spectral index has relatively small impact on derived SFRs because our observed 1.4 GHz data probe close to the rest-frame 1.4 GHz, at which the flux–SFR conversion is calibrated. Namely, if we assumed a flat index $\alpha = 0$, then we would obtain SFRs $\sim$ 25%–40% lower at $z = 0.5$–1. On the other hand, if we assumed a steeper value $\alpha = -1$ (or -1.5), then we would obtain SFRs $\sim$ 10%–20% ($\sim$35%–70%) higher at $z = 0.5$–1.

The limit on the SFR of the GRB 980425 host based on 8.64 GHz data is not consistent with the value derived from the 4.80 GHz data because, for consistency, a spectral slope of $\alpha = -0.75$ was assumed, whereas in reality it is steeper (see Michałowski et al. 2009; Section 5.5).

In order to assess the amount of the dust attenuation in GRB hosts we compared their SFRs derived from the UV emission ($\mathrm{SFR}_{\mathrm{UV}}$) with $\mathrm{SFR}_{\mathrm{radio}}$. In Table 2 we compiled the $\mathrm{SFR}_{\mathrm{UV}}$ (mostly from 0.28 μm continuum data) from the literature (Castro Cerón et al. 2010; Savaglio et al. 2009; Christensen et al. 2004; Jakobsson et al. 2012; Ovaldsen et al. 2007; Svensson et al. 2010). The de-reddened SFRs given by Savaglio et al. (2009) were reddened based on their reported A_V. For the hosts of GRB 051016B, 051117B, 060814, and 070318 we calculated the $\mathrm{SFR}_{\mathrm{UV}}$ from V-, B-, and R-band fluxes, respectively, reported by Ovaldsen et al. (2007) and Malesani et al. (2012), which correspond to the rest-frame UV emission at the redshifts of the hosts. For the hosts of GRB 040924 and 061021 there are no UV continuum data available, so we calculated $\mathrm{SFR}_{[\mathrm{O\,II}]}$ from the flux reported by Wiersema et al. (2008) and Jakobsson et al. (2012), respectively, applying the conversion of Kewley et al. (2004, their Equation (4)).

We assume that $\mathrm{SFR}_{\mathrm{radio}}$ reflects the total amount of star formation in GRB hosts. Hence, an approximate estimate of the dust attenuation in the ultraviolet may be obtained by dividing the radio SFR and $\mathrm{SFR}_{\mathrm{UV}}$:

$$A_{\mathrm{UV}} = 2.5 \log \frac{\mathrm{SFR}_{\mathrm{radio}}}{\mathrm{SFR}_{\mathrm{UV}}} \ \mathrm{mag}. \quad (1)$$

The resulting attenuations are presented in Table 2. The uncertainties of $\mathrm{SFR}_{\mathrm{radio}}$ and $\mathrm{SFR}_{\mathrm{UV}}$ are of the order of a factor of two (Bell 2003; Kennicutt 1998), so the uncertainties of the A_{UV} estimates are of the order of a factor of $2\sqrt{2} \sim 2.8$ ($\sim$1.1 mag).

[21] Defined as $F_\nu \propto \nu^\alpha$, i.e., $\alpha_{\nu_1}^{\nu_2} = \log[F_\nu(\nu_2)/F_\nu(\nu_1)]/\log(\nu_2/\nu_1)$.

5. DISCUSSION

5.1. The ULIRG Nature of the Host of GRB 021211

Our 1.43 GHz detection of the host of GRB 021211 ($\sim 10\sigma$) corresponds to SFR of $\sim 825\,M_\odot\,\mathrm{yr}^{-1}$ (Table 2), which places it in the category of ultraluminous infrared galaxies (ULIRGs; $L_{\mathrm{IR}} > 10^{12}\,L_\odot$, or SFR $\gtrsim 172\,M_\odot\,\mathrm{yr}^{-1}$ using the conversion of Kennicutt 1998). This is the highest SFR ever reported for a GRB host (compare with Berger et al. 2003a, 2001; Michałowski et al. 2008; Stanway et al. 2010; Watson et al. 2011).

Because of this unusually high SFR, we present the investigation of the data quality for this object. We verified that the source is not due to an uncleaned bright source nearby. Moreover, the astrometry of our VLA map and the VLT image (Della Valle et al. 2003) are consistent. Namely, for three radio sources that are detected in the optical image[22] we measured the mean offsets between the radio and optical positions consistent with zero: $\Delta\alpha = -0\farcs27 \pm 0\farcs32$ and $\Delta\delta = 0\farcs14 \pm 0\farcs39$. Finally, the median ratio of fluxes of bright objects detected in our radio map to the fluxes reported in the NRAO VLA Sky Survey (Condon et al. 1998) is $\sim 1.19^{+0.31}_{-0.36}$, confirming the accuracy of the flux calibration.

However, our detection is inconsistent with a non-detection at 2.1 GHz presented by Hatsukade et al. (2012; $S_{2.1} < 34.2\,\mu$Jy at 3σ) as it implies an extremely steep (and unphysical) spectral index $\alpha^{2.10}_{1.43} < -5.9$. Extrapolating from our 1.43 GHz detection, the expected signal at 2.1 GHz would be $\sim 250\,\mu$Jy assuming $\alpha = -0.75$. However, the equatorial declination of GRB 021211 of $+6^\circ 44'$ makes it difficult to observe it using east–west arrays, such as ATCA, as the beam is highly elongated, i.e., $2'' \times 51''$ at 2.1 GHz. This may pose some problems in the detection of sources, and indeed in our VLA map we have found two additional sources[23] with 1.43 GHz fluxes of ~ 650 and $350\,\mu$Jy, respectively, which are not detected in the 2.1 GHz ATCA map of Hatsukade et al. (2012). Further observations at various radio frequencies are needed to resolve this issue.

Our 1.43 GHz detection is consistent with the (sub)millimeter limits of Smith et al. (2005) and Priddey et al. (2006). Namely, they did not detect the host of GRB 021211 at $850\,\mu$m (0.3 ± 1.9 mJy) and 1.2 mm (0.07 ± 0.53 mJy), respectively. The $850\,\mu$m limit implies a submillimeter-to-radio spectral index $\alpha^{350}_{1.4} < 0.53$, consistent with most of the models presented by Carilli & Yun (1999, 2000, their Figures 1 and 3, respectively). Assuming spectral energy distribution (SED) templates of Arp 220 and M82 (Silva et al. 1998), the 1.2 mm limit corresponds to a 3σ limit of SFR $\lesssim 700$–$1100\,M_\odot\,\mathrm{yr}^{-1}$ (for the $850\,\mu$m limit these estimates are $\sim 30\%$ higher), consistent with our radio SFR $\sim 825\,M_\odot\,\mathrm{yr}^{-1}$ (Table 2). However, this 1.2 mm flux limit corresponds to an SFR $\sim$ 100–500 $M_\odot\,\mathrm{yr}^{-1}$ for many other SED templates (Silva et al. 1998; Iglesias-Páramo et al. 2007; Michałowski et al. 2008, 2010a). Hence, deeper (sub)millimeter observations (rms $\sim$ 0.1–0.2 mJy) are needed to verify if our radio detection is inconsistent with (sub)millimeter data, which would indicate a significant AGN contribution to the radio flux of the host of GRB 021211.

5.2. Star Formation Rates of the GRB Host Population

The SFRs of GRB hosts are shown as a cumulative distribution on Figure 3. The high-SFR boundaries were calculated using the radio detections and upper limits, whereas the low-SFR boundaries were obtained by substituting the radio SFR upper limits with the lower limits from the UV. We found that at least $\sim 63\%$ ($\geqslant 15/24$)[24] of all our GRB hosts at $z \lesssim 1$ have SFR $< 100\,M_\odot\,\mathrm{yr}^{-1}$ and only $\lesssim 8\%$ ($\leqslant 2/24$)[25] could have SFR $> 500\,M_\odot\,\mathrm{yr}^{-1}$. This implies that it is rare ($\lesssim 33\%$ chance, $\leqslant 8/24$)[26] for a GRB to reside in an ULIRG. This is consistent with the contribution of ULIRGs to the cosmic star formation history being $< 10\%$ at $z < 1$ (Le Floc'h et al. 2005).

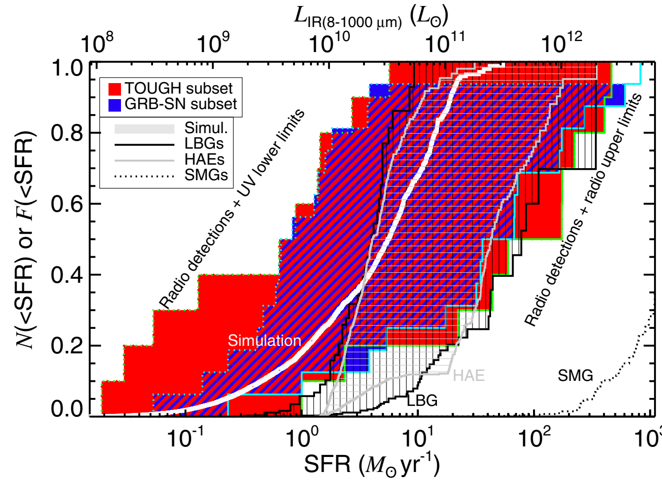

Figure 3. Cumulative distribution of SFRs of GRB hosts in the $z < 1$ TOUGH unbiased (red area) and the GRB-SN (blue area) subsets. The high-SFR boundaries (colored solid lines) are constructed using the detections and limits of $\mathrm{SFR_{radio}}$ (Table 2), whereas the low-SFR boundaries (colored dotted lines) are constructed using the $\mathrm{SFR_{UV}}$ for galaxies not detected in the radio. The upper x-axis gives the corresponding infrared luminosity according to $\mathrm{SFR}(M_\odot\,\mathrm{yr}^{-1}) = 1.72 \times 10^{-10} L_{\mathrm{IR}}(L_\odot)$ (Kennicutt 1998). We found that at least $\sim 63\%$ ($\geqslant 15/24$) of GRB hosts at $z \lesssim 1$ have SFR $< 100\,M_\odot\,\mathrm{yr}^{-1}$ and only $\lesssim 8\%$ ($\leqslant 2/24$) could have SFR $> 500\,M_\odot\,\mathrm{yr}^{-1}$. For comparison, the SFR distributions of $z = 0.51$ simulated galaxies (Croton et al. 2006), $z \sim 1$ Lyman break galaxies (LBG; Basu-Zych et al. 2011), $z \sim 0.84$ Hα emitters (HAE; Sobral et al. 2009), and $z \sim$ 2–3 submillimeter galaxies (SMGs; Michałowski et al. 2010a, 2010b) are shown (labeled lines, of which the right lines represent dust-corrected SFRs). These distributions were weighted by SFR (so they reflect the fraction of total star formation in the sample contributed by galaxies with SFRs lower than a given SFR) to allow a comparison with the GRB host population, which is likely selected based on SFRs (see Section 5.3). It is evident that current SFR limits imply that the GRB host population is consistent with star-forming galaxies at similar redshifts (simulated, LBGs, and HAEs) and is inconsistent with SMGs. Since we did not detect most of the targets, the distributions of the $z < 1$ TOUGH unbiased and GRB-SN subsets are consistent (the overlap of the blue and red areas is significant).

(A color version of this figure is available in the online journal.)

Even though high star-forming GRB hosts are rare at $z \lesssim 1$, the SFR of GRB 021211 alone constitutes as much as $\sim 22\%$ of the summed SFR of all $z \lesssim 1$ GRB hosts, even when we sum over radio upper limits (and hence its contribution is higher in reality). Hence, such high star-forming GRB hosts likely dominate the contribution of this population to the cosmic star formation history.

The average radio SFR of GRB hosts can be assessed using the average radio flux of the GRB hosts undetected in our radio observations. For each host we converted the flux at the GRB position at the observed frequency to that at the rest-frame 1.43 GHz, using a radio spectral index of -0.75. In this way, we obtained a weighted mean of the flux equal to $-13 \pm 16\,\mu$Jy.

[22] With the following radio R.A. and decl.: 08:09:01.315, +06:43:03.91; 08:09:12.842, +06:43:54.53; and 08:09:11.746, +06:44:05.87.

[23] With the following VLA R.A. and decl.: 08:09:10.992, +06:41:26.20; and 08:09:31.704, +06:41:58.00.

[24] $\geqslant 50\%$ ($\geqslant 5/10$) for TOUGH subset only.

[25] 0% (0/10) for TOUGH subset only.

[26] $\leqslant 50\%$ ($\leqslant 5/10$) for TOUGH subset only.

Hence, we did not detect the GRB host population even when averaging the data. At least such level of rms has to be reached in future GRB host surveys to obtain significant number of detections. At the mean redshifts of these hosts, $z = 0.53$, this corresponds to a 3σ upper limit of $\mathrm{SFR_{radio}} < 15\,M_\odot\,\mathrm{yr}^{-1}$. Hence, the general population of GRB hosts is below the LIRG limit ($L_\mathrm{IR} < 10^{11}\,L_\odot$, or $\mathrm{SFR} \lesssim 17.2\,M_\odot\,\mathrm{yr}^{-1}$ using the conversion of Kennicutt 1998). It is expected that LIRGs do not dominate our GRB host sample, because LIRGs dominate the cosmic star formation history only above $z \sim 0.7$ (with their contribution rising to ∼70% at $z = 1$, Le Floc'h et al. 2005; and staying at this level at least up to $z \sim 2.3$, Magnelli et al. 2011).

The full ALMA with 50 antennas will reach an rms sensitivity of ∼0.023 mJy at 345 GHz in 1 hr.[27] This corresponds to $\mathrm{SFR} \sim 5$–$20\,M_\odot\,\mathrm{yr}^{-1}$ at $z = 10$ (using SED templates of Silva et al. 1998; Iglesias-Páramo et al. 2007; Michałowski et al. 2008, 2010a), so ALMA will easily detect GRB hosts basically at any redshift within a few hours because the UV lower limits on SFRs are of the order of $\sim 1\,M_\odot\,\mathrm{yr}^{-1}$ (Table 2).

To summarize, the overall picture is that $z \lesssim 1$ GRB hosts have modest SFRs (as suggested by Stanway et al. 2010), but a small fraction (∼4%–8%) of them have undergone an extreme star formation episode. However, the latter claim suffers from poor number statistics.

5.3. The Relation to Other Galaxies: Do GRBs Trace Star Formation in an Unbiased Way?

In order to investigate whether the GRB host population is consistent with the general population of star-forming galaxies at similar redshifts, we show their SFR distribution on Figure 3. The comparison to other galaxies must be done carefully, because the probability that a galaxy with given SFR is included in a usual galaxy sample depends only on the number density of such objects (as long as this SFR corresponds to a flux higher than the sample selection threshold). This is not the case for a GRB host sample, because, assuming that GRBs trace star formation in an unbiased way, a galaxy with higher SFR is more likely to host a GRB and, in turn, to be selected into the GRB host sample (e.g., Natarajan et al. 1997; Fynbo et al. 2001). In order to account for this, we weighted the cumulative distributions of other galaxies by their SFRs, i.e., the curves for other galaxies correspond to the fraction of total star formation in the sample contributed by galaxies with SFRs lower than a given SFR.

It is apparent from Figure 3 that the SFR distributions of GRB hosts and of simulated galaxies at $z = 0.51$ (Croton et al. 2006),[28] produced in a semianalytical model and based on the Millenium Simulation (Springel et al. 2005), are fully consistent.

Similarly, the SFR distribution of $z \lesssim 1$ GRB hosts is consistent with that of $z \sim 1$ Lyman break galaxies (LBGs; from Basu-Zych et al. 2011, SFRs from 24 μm and rest-frame UV photometry) and $z \sim 0.84$ Hα emitters (HAEs; from Sobral et al. 2009, SFRs from 24 μm photometry and Hα fluxes). We note that the median stellar masses of these LBGs ($M_* \sim 10^{9.5}\,M_\odot$; Basu-Zych et al. 2011) and HAEs ($M_* \sim 10^{10.1}\,M_\odot$; Sobral et al. 2011) are also consistent with that of GRB hosts ($M_* \sim 10^{9.3-9.7}\,M_\odot$; Castro Cerón et al. 2010; Savaglio et al. 2009). Moreover, as shown in Section 5.4, the dust attenuation we derived for GRB hosts is consistent with that of LBGs and HAEs.

An apparent inconsistency at low SFRs of the GRB host samples with the LBG and HAE populations (the GRB population extends to lower SFRs) is an effect of higher flux detection threshold for the latter. Namely, the limiting magnitude for LBGs of $u < 24.5$ mag corresponds to $\mathrm{SFR} > 0.5\,M_\odot\,\mathrm{yr}^{-1}$, whereas the limiting luminosity for HAE of $L_{\mathrm{H}\alpha} > 10^{41.5}$ erg s^{-1} corresponds to $\mathrm{SFR} > 2.5\,M_\odot\,\mathrm{yr}^{-1}$. Hence, galaxies with $\mathrm{SFR} < 0.5\,M_\odot\,\mathrm{yr}^{-1}$ are not present in the LBG and HAE samples because they are below the detection limits. Indeed, when we restricted the simulated galaxies (which are consistent with the GRB host population) to galaxies above these limits, their distributions are consistent with those of LBGs and HAEs.

A Kolmogorov–Smirnov (K-S) test resulted in a probability of ∼15% that the UV SFRs of all our GRB hosts and $z < 1$ LBGs are drawn from the same population. However, for $z \sim 0.84$ HAEs such probability is negligible ($\sim 10^{-11}$), showing that HAEs have systematically higher UV SFRs than GRB hosts. Figures 2 and 3 show that our current limits on the radio SFRs of GRB hosts are not deep enough to test whether the total SFRs of HAEs are also higher than that of GRB hosts.

As shown in Figure 3, the SFRs of the $z \lesssim 1$ GRB hosts are clearly inconsistent with those of submillimeter galaxies (SMGs), dusty high star-forming $z \sim 2$–3 galaxies (Michałowski et al. 2010a, 2010b; SFRs from total infrared emission and rest-frame UV photometry), even when only radio upper limits for GRB hosts are taken into account (colored solid lines). This is also expected from the fact that GRB hosts are much less massive ($M_* \sim 10^{9.3-9.7}\,M_\odot$; Castro Cerón et al. 2010; Savaglio et al. 2009) than SMGs ($M_* \sim 10^{10.4-11.3}\,M_\odot$; Borys et al. 2005; Michałowski et al. 2010a, 2012; Hainline et al. 2011; Bussmann et al. 2012; Yun et al. 2012). We note, however, that the stellar mass estimates for GRB hosts are based on samples biased against dusty galaxies, so the general population of GRB hosts may include galaxies as massive as SMGs.

The inconsistency of the $z \lesssim 1$ GRB host and SMG populations is also revealed by the K-S test giving a negligible probability of $\sim 10^{-8}$ that the UV SFRs of GRB hosts and SMGs are drawn from the same population. If we restrict the analysis to $z < 1$ SMGs then the probability increases to ∼63% (consistent samples), but these $z < 1$ SMGs have a median $\mathrm{SFR_{IR}} \sim 60\,M_\odot\,\mathrm{yr}^{-1}$, very close to our limits of $\mathrm{SFR_{radio}}$ for GRB hosts, so if GRB hosts are similar to $z < 1$ SMGs, then the majority of them would need to be just below the detection limits, which is unlikely.

We note that the comparison between GRB hosts, SMGs, LBGs, and HAEs involves SFRs derived from the radio, 24 μm, total infrared, UV, and Hα luminosities, but we do not expect any systematic offset between these estimates. Namely, Elbaz et al. (2010, their Figure 2) showed that the observed 24 μm luminosity is correlated with the total infrared luminosity, which, in turn, is correlated with the radio luminosity (Condon 1992). Similarly, Wijesinghe et al. (2011, their Figure 8) showed that SFRs from Hα and UV are well correlated.

To summarize, our data allow a significant range of SFRs for $z \lesssim 1$ GRB hosts, so their distribution is consistent with that of the general population of galaxies (at least with LBGs and simulated galaxies) having a median SFR of a few $M_\odot\,\mathrm{yr}^{-1}$. If this conclusion is confirmed in deeper radio observations, it would indicate that GRBs trace a large fraction of the overall star formation, and are therefore less biased indicators than once thought. On the other hand, if deeper radio observations reveal that the total SFRs of GRB hosts are very close to their UV

[27] Assuming fourth octile of water vapor; http://almascience.eso.org/call-for-proposals/sensitivity-calculator.

[28] http://tao.it.swin.edu.au/mock-galaxy-factory/

SFRs, then GRB hosts will not be consistent with tracing the overall population of star-forming galaxies.

Indeed, there are some indications that GRB hosts are different than other galaxies at similar redshifts. Previous studies have showed that GRB hosts are metal poor (Fynbo et al. 2003; Prochaska et al. 2004; Gorosabel et al. 2005; Sollerman et al. 2005; Hammer et al. 2006; Stanek et al. 2006; Wiersema et al. 2007; Christensen et al. 2008; Modjaz et al. 2008, 2011; Levesque et al. 2010a, 2010b; Leloudas et al. 2011), fainter, and more compact than SN hosts, as well as that GRBs themselves are much more concentrated in the UV-bright regions of their hosts than SNe (Fruchter et al. 2006; Bloom et al. 2002). Moreover, Wainwright et al. (2007, their Figures 3 and 6) found that in the $z < 1$ GRB host population the ratio of irregular to regular galaxies is 2:1, different than 1:2 for field galaxies; and that GRB hosts are a factor of two smaller than field galaxies. This suggests a potential bias in the GRB host population (though all these studies were based on optically biased GRB host samples).

However, Leloudas et al. (2010, their Figure 3) showed that the distribution of GRBs within their hosts is in fact consistent with that of type-Ic SNe and of Wolf–Rayet stars, whereas Svensson et al. (2010, their Table 3 and Figure 8) did not find any significant difference between the absolute magnitudes of GRB and SN hosts. Moreover, Fynbo et al. (2006, their Figure 2) and Savaglio et al. (2009, their Figure 18) showed that the metalicity of GRB hosts is consistent with (or even higher than; see also Savaglio et al. 2012) that of damped Lyα systems at corresponding redshifts. Similarly, Levesque et al. (2010c) found that some GRBs explode in metal-rich environments. Moreover, optically dark GRBs, missed in most previous studies, were claimed to be hosted in more dusty and metal-rich hosts (Perley et al. 2009; Greiner et al. 2011; Hunt et al. 2011; Krühler et al. 2011; Svensson et al. 2012). Finally, Conselice et al. (2005) found that GRB hosts are smaller than field galaxies, but only at $z < 1.2$; and that these two populations at $z < 1$ are consistent with regards to their concentrations and asymmetries. Hence, the biases of the GRB host sample in terms of morphology and metallicity are far from being well understood.

Regarding observational biases, Fynbo et al. (2009) showed that the GRB host sample selected based on a requirement of an optical spectroscopic redshift is not representative for all GRBs, likely biased against dusty objects. Moreover, SNe exploding in (U)LIRGs are expected to be highly extinguished by dust (Mattila et al. 2004, 2007; Melinder et al. 2012), implying that samples of optically selected GRBs may completely miss those exploding in high star-forming galaxies. However, Figure 3 does not reveal any differences between the radio properties of the optically biased pre-*Swift* sample of GRB-SN hosts and those of the $z < 1$ TOUGH unbiased subset. Namely, the high-SFR bounds of the distributions are similar. This is mainly because we did not detect the majority of the targets and the limiting depths were similar. Similarly, the K-S test resulted in 40% probability that the SFR_{UV} for the TOUGH and GRB-SN subsets are drawn from the same parent population. Larger samples and deeper radio data are necessary to investigate this issue.

5.4. Ultraviolet Attenuation

The cumulative distribution of the dust attenuation is shown on Figure 4. It should be seen as an upper limit, because it is based mostly on radio non-detections. We found that $\gtrsim$88%

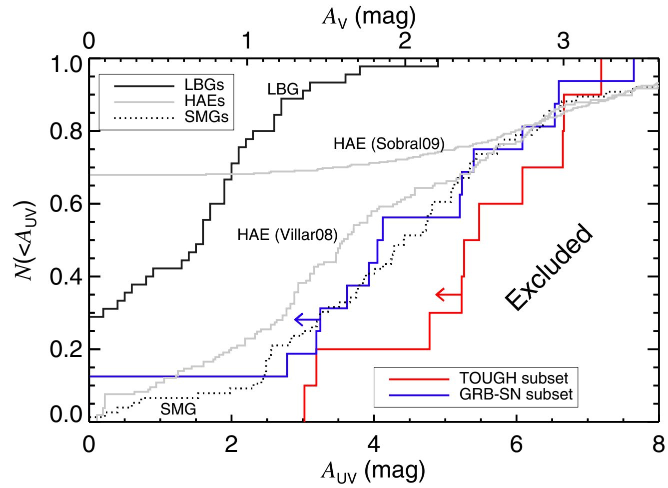

Figure 4. Cumulative distribution of ultraviolet (and optical) dust attenuation of GRB hosts in the $z < 1$ TOUGH unbiased (red solid line) and GRB-SN (blue solid line) subsets. Since the distributions are mostly based on radio non-detections they should be taken as upper limits to A_{UV}, i.e., the area to the right of the lines is ruled out by the data. The upper x-axis was derived by assuming an SMC extinction curve ($A_{UV} = 2.22\,A_V$; Gordon et al. 2003). We found that $\gtrsim$88% ($\geqslant$21/24) of the GRB hosts have $A_{UV} < 6.7$ mag, i.e., $A_V < 3$ mag. For comparison, the distributions of $z \sim 1$ Lyman break galaxies (LBG; Basu-Zych et al. 2011), $z \sim 0.84$ Hα emitters (HAE; Villar et al. 2008; Sobral et al. 2009), and $z \sim 2$–3 submillimeter galaxies (SMGs; Michałowski et al. 2010a, 2010b) are shown (labeled black lines). The attenuation at Hα was converted to that in the ultraviolet by assuming an SMC extinction curve ($A_{UV} = 1.78\,A_{H\alpha}$; Gordon et al. 2003). The distributions for GRB hosts are consistent with those of LBGs and HAEs, yet likely inconsistent with that of SMGs.

(A color version of this figure is available in the online journal.)

($\geqslant$21/24)[29] GRB hosts at $z \lesssim 1$ have $A_{UV} < 6.7$ mag, i.e., $A_V < 3$ mag assuming a Small Magellanic Cloud (SMC) extinction curve ($A_{UV} = 2.22\,A_V$; Gordon et al. 2003). This is consistent with the previous observational (Kann et al. 2006; Schady et al. 2007, 2010, 2012; Kann et al. 2010; Savaglio et al. 2009; Han et al. 2010; Liang & Li 2010; Greiner et al. 2011; Watson 2011; Watson & Jakobsson 2012; Zafar et al. 2010, 2011) and theoretical (Lapi et al. 2008; Mao 2010) results that GRB hosts are weakly obscured by dust with very few exceptions (Tanvir et al. 2004, 2008; Castro Cerón et al. 2006; Le Floc'h et al. 2006; Michałowski et al. 2008; Küpcü Yoldaş et al. 2010; Hunt et al. 2011; Krühler et al. 2011; Svensson et al. 2012). This result is also confirmed for the entire TOUGH sample (Hjorth et al. 2012), which is *not* biased against dusty systems. Our finding is also consistent with a fraction of 5%–36% of core collapse SNe in normal galaxies with $A_V > 3.7$ mag (Section 2.4 of Mattila et al. 2012).

It has been claimed that dust is responsible for the optical faintness of the so-called dark GRBs, i.e., those with optical-to-X-ray spectral index $\beta_{OX} < 0.5$ (Ramirez-Ruiz et al. 2002; Jakobsson et al. 2004; Perley et al. 2009; Greiner et al. 2011; Krühler et al. 2011). None of our $z \lesssim 1$ GRBs were dark (Jakobsson et al. 2004; Butler et al. 2005; Fynbo et al. 2009; Xu et al. 2009; though there is no X-ray data for four pre-*Swift* GRBs in our sample). Hence, none of the afterglows of the GRBs in our $z \lesssim 1$ sample seem to be particularly dust-obscured (though the effect of dust at $z < 1$ is less severe than at higher redshifts, i.e., for the same amount of dust a GRB at higher redshift may be classified as "dark," because the observed-frame optical emission corresponds to the UV wavelengths strongly affected by dust). This is consistent with low levels of dust

[29] $\geqslant$80% ($\geqslant$8/10) for TOUGH subset only.

attenuation we find for their hosts, but we note that, in principle, the spatially integrated attenuation of a host reported here may be inconsistent with the line-of-sight extinction derived from an afterglow, as the latter probes dust distributed only over a narrow opening angle.

GRB 021211, with a radio-detected host, was initially called "dark" due to its optical faintness (Crew et al. 2003; Fox et al. 2003; Li et al. 2003), but the lack of X-ray data makes it impossible to classify it according to the more rigorous β_{OX} definition. However, Fox et al. (2003) found that the optical afterglow was not severely reddened, so the GRB must have occurred away from the highly dust-attenuated regions suggested by our radio detection.

We also note that only $\lesssim$50% of all our GRB hosts at $z \lesssim 1$ could have $A_V > 2$ mag ($A_{UV} > 4.4$ mag), i.e., similar dust attenuation levels to that in SMGs (Smail et al. 2004; Swinbank et al. 2004; Borys et al. 2005; Michałowski et al. 2010a, 2010b; Hainline et al. 2011). Indeed, in Figure 4 we show that the A_{UV} distribution for SMGs (from Michałowski et al. 2010a, 2010b) displays high attenuation levels, very likely inconsistent with that of $z \lesssim 1$ GRB hosts, given that the lines for GRB hosts represent upper limits on dust attenuation. This is consistent with a tendency that the presence of a GRB typically selects dwarf galaxies that are generally less dusty. However, the most star-forming GRB hosts may contain significant amounts of dust, comparable to those of SMGs (as suggested by Michałowski et al. 2008).

In Figure 4, we also show the attenuation distribution of $z \sim 1$ LBGs from Basu-Zych et al. (2011). Our GRB host distribution is mostly based on upper limits on A_{UV}, but it is clear that these two distribution may be consistent, i.e., the fraction of objects with very low dust attenuation is similar (∼20–30%) and the LBG distribution is always below that of the GRB hosts. Deeper radio or far-IR data would be necessary to confirm that these samples are truly consistent. If this is the case, then we can expect a median $A_{UV} \sim 1.6$ mag for GRB hosts and therefore that their SFR_{radio} should be, on average, a factor of ∼4 higher than their SFR_{UV}. Assuming a typical $SFR_{UV} = 1\,M_\odot\,yr^{-1}$, then the $SFR_{radio} = 4\,M_\odot\,yr^{-1}$ corresponds to the observed-frame 1.43 GHz fluxes of 33, 8, and 3 μJy at $z = 0.3$, 0.6, and 1.0, respectively. Hence, if the attenuation of GRB hosts is indeed similar to that in LBGs, then current radio interferometers (including EVLA) will struggle to detect them beyond $z = 0.6$.

For HAE, we converted the attenuation at Hα to that at the UV assuming an SMC extinction curve ($A_{UV} = 1.79\,A_{H\alpha}$; Gordon et al. 2003). The comparison with the dust attenuation of GRB hosts and HAEs is less clear. The sample of Villar et al. (2008) contains much fewer galaxies with very low attenuation compared to the $z \lesssim 1$ GRB host sample, but this is not the case for the sample of Sobral et al. (2009). In any case, in order for a GRB host sample to be consistent with the HAE sample, the attenuation of the hosts with current limits at $A_{UV} \sim 5$–7 mag would need to be very close to these limits.

5.5. Radio Spectral Indices

The radio spectral index of the host of GRB 980425 turned out to be very steep ($\alpha_{4.8}^{8.64} < -1.44$; Michałowski et al. 2009) and was interpreted as a sign of the dominant old stellar population. Similarly, for the GRB 021211 host, using our detection at 1.43 GHz and the upper limit of 45 μJy at 8.46 GHz reported by Fox et al. (2003) we derive a steep $\alpha_{1.43}^{8.64} < -1.12$.

On the other hand, the spectral index of the GRB 031203 host is flatter $\alpha_{1.39}^{2.37} = -0.53 \pm 0.50$. This suggests a higher contribution of free–free emission (or synchrotron self-absorption; Condon 1992) and, hence, younger stellar population (Bressan et al. 2002; Cannon & Skillman 2004; Hirashita & Hunt 2006; Clemens et al. 2008). This value is also consistent within errors with the spectral slopes of $\alpha \sim -0.7$ to -0.8 found for star-forming galaxies both local and at high redshifts (Condon 1992; Dunne et al. 2009; Ibar et al. 2010).

6. CONCLUSIONS

We present radio continuum data for a sample of 30 GRB hosts including 22 new observations. We detected three targets. The derived limits on the SFRs show that at least ∼63% of the GRB hosts have SFR $< 100\,M_\odot\,yr^{-1}$ and that at most ∼88% of GRB hosts have $A_{UV} < 6.7$ mag, i.e., $A_V < 3$ mag. The average flux of non-detected hosts at $z \sim 0.5$ sets an upper limit of SFR $< 15\,M_\odot\,yr^{-1}$. Using our radio data in conjunction with the rest-frame ultraviolet data, we found that the distributions of SFRs and ultraviolet attenuations of GRB hosts are consistent with those of other star-forming galaxies at $z \lesssim 1$. This is consistent with the hypothesis that GRBs trace cosmic star formation, but further studies of morphology and metallicities of GRB hosts are required to understand potential biases in this sample.

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Facilities: ATCA, GMRT, VLA, WSRT

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