ANOTHER SHORT-BURST HOST GALAXY WITH AN OPTICALLY OBSCURED HIGH STAR FORMATION RATE: THE CASE OF GRB 071227

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ABSTRACT

We report on radio continuum observations of the host galaxy of the short gamma-ray burst 071227 (z = 0.381) with the Australia Telescope Compact Array. We detect the galaxy in the 5.5 GHz band with an integrated flux density of $F_{\nu} = 43 \pm 11 \mu$Jy, corresponding to an unobscured star-formation rate of about $24 M_{\odot} \text{yr}^{-1}$, 40 times higher than what was found from optical emission lines. Among the ~30 well-identified and studied host galaxies of short bursts this is the third case where the host is found to undergo an episode of intense star formation. This suggests that a fraction of all short-burst progenitors hosted in star-forming galaxies could be physically related to recent star formation activity, implying a relatively short merger timescale.

Key word: gamma-ray burst: individual (GRB 071227)

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1. INTRODUCTION

Gamma-ray bursts (GRBs) are divided into long/soft and short/hard, with the borderline at 2 s (Kouveliotou et al. 1993). Other more physically motivated indicators to classify GRBs have been proposed (e.g., Zhang et al. 2009), but this division between long/soft and short/hard is still a widely used classification. It is commonly accepted that long GRBs are linked to the collapse of very massive stars (for a review, see Woosley & Bloom 2006; Hjorth & Bloom 2012), while short GRBs are linked to the collapse of compact stars. Individual and qualitative age estimates of the progenitor can be obtained if a host galaxy can be identified. Even though there is still a substantial fraction of hostless short-burst afterglows (Tunnillie et al. 2014), for more than 50% of all well-localized events host galaxies have been found. While in elliptical galaxies at $z \lesssim 1$ the GRB progenitors are most likely members of an old stellar population, in star-forming galaxies they could also be young. In fact, short-burst progenitors are found to be hosted by galaxies of all morphological types (e.g., Leibler & Berger 2010; Fong & Berger 2013; Fong et al. 2013) and stellar evolution models suggest a broad range in the ages of merging binaries, reaching from tens of millions to billions of years (Belczynski et al. 2006).

Star-formation rates (SFRs) in GRB host galaxies are usually derived from measured emission line fluxes, e.g., [O II] in case of redshifts $z \lesssim 1$. These measurements suffer, however, from the unknown extinction in these galaxies and, therefore, represent only a lower limit on the present SFR. On the other hand, radio observations are unaffected by extinction and provide an unobscured view on the star-forming activity in a galaxy via synchrotron radiation from electrons accelerated in supernova (SN) remnants, though over a relatively broad time span of about 100 million years. Consequently, in recent years radio observations of the host galaxies of long GRBs have been undertaken with the goal to derive the unobscured SFR based on the measured radio continuum flux (Berger et al. 2003; Stanway et al. 2010; Hatsukade et al. 2012; Michalowski et al. 2012; Perley & Perley 2013). In most cases the hosts of long bursts could not be detected at radio wavelengths, with typical limits ranging from $\lesssim 10 M_{\odot} \text{yr}^{-1}$ for low-redshift hosts to $\lesssim 1000 M_{\odot} \text{yr}^{-1}$ for high-redshift hosts; only in ~10 cases are SFRs found to be $\sim 100 M_{\odot} \text{yr}^{-1}$. Since in most cases these galaxies have optically deduced SFRs of at most few $M_{\odot} \text{yr}^{-1}$, radio observations might simply not have gone deep enough to detect them (still leaving room for a substantial optically hidden SFR).

In contrast to increasing attempts to explore the hosts of long bursts in the radio band, no systematic radio investigation of the hosts of short bursts has yet been performed. The only exception is a single deep radio observation (and detection) of the host of the short GRB 120804A at $z = 1.3$ (Berger et al. 2013). In all other cases, derived SFRs are based on optical emission lines. However, it is entirely possible that the hosts of several short bursts are also affected by internal extinction, possibly resulting in a substantial underestimation of the derived SFRs. Like long GRBs, short-burst afterglows can, in principle, be used to derive host extinction based on multi-color afterglow data (e.g., Kann...
et al. 2011; Nicuesa Guelbenzu et al. 2012). Nevertheless, such an approach is in any case limited to the line of sight toward the GRB progenitor and is not necessarily representative for the global host-galaxy extinction.

The host of the short burst 071227 is well-suited as a radio target in this respect. While the afterglow of GRB 071227 is known only from a single detection in the $R_C$ band, and no line-of-sight extinction $A_V$ could be derived, optical broadband photometry of its host galaxy suggests a high internal $A_V$ (Leibler & Berger 2010). Also, the galaxy is relatively closeby ($z = 0.381 \pm 0.001$; D’Avanzo et al. 2009), hinting at its potential detection in the radio band.

GRB 071227 triggered Swift/BAT and had a duration of $T_{90}(15–350$ keV) = $1.8 \pm 0.4$ s (Sakamoto et al. 2007a; Sato et al. 2007). Its intense first spike was followed by extended soft emission lasting for $\sim 100$ s (Sakamoto et al. 2007b). The burst was also detected by Konus-Wind (Golenetskii et al. 2007; duration $\sim 1.7$ s) and Suzaku-WAM (Onda et al. 2008; $T_{90} \sim 1.5$ s). Swift/XRT localized a bright X-ray afterglow (Beardmore et al. 2007); Swift/UVOT revealed a single faint source near the XRT error circle, which was identified as a galaxy also visible in the DSS (Berger et al. 2007). Later observations revealed that the galaxy is an edge-on, late-type galaxy (D’Avanzo et al. 2009). The optical afterglow was situated at a projected distance of about 15 kpc away from the galactic nucleus, close to the galactic plane. Its SFR was determined via the observed \text{[O II]} line flux to be a modest $\sim 0.6 M_\odot$ yr$^{-1}$ (D’Avanzo et al. 2009).

Here we report on radio continuum observations of the GRB host galaxy with the aim to measure its unobscured SFR. Throughout the paper, we adopt a $\Lambda$CDM cosmology with $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$, and $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$ (Spergel et al. 2003). At the given redshift of $z = 0.381$ a value of 1$^\prime$ corresponds to a projected distance of 5.2 kpc.

2. OBSERVATIONS AND DATA REDUCTION

Radio continuum observations of the host of GRB 071227 were performed on 2013 July 26/27 in the 5.5 and 9.0 GHz bands (corresponding to 6 and 3 cm) with the Australia Telescope Compact Array (ATCA) using the upgraded Compact Array Broadband Backend (CABB) detector (Wilson et al. 2011) and all six 22 m antennae with the 6 km baseline (program ID: C2840). In this configuration the width of the primary beam is 9 (at 5.5 GHz) and 5 arcmin (9.0 GHz), respectively (ATCA users guide\textsuperscript{10}), and the synthesized beam sizes are $\approx 2.3 \times 2.9$ and $\approx 1.4 \times 1.8$, at 6 and 3 cm, respectively. CABB integrates in both bands simultaneously with 2048 channels, beginning at 4.476 and 7.976 GHz, respectively, with an increment of 1 MHz. Bandpass and flux calibration was performed by observing PKS B1934–638 for 10 min at the beginning of the observing run. Phase calibration was done by observing the source 0308–611 for 3 minutes every hour followed by 57 minute integrations on target. Altogether 11 such 1 hr cycles were executed, in total covering nearly a complete ($u, v$) plane.

Data reduction was performed using MIRIAD version 1.5 for ATCA radio interferometry.\textsuperscript{11} All data were cleaned from radio frequency interference (RFI) using the pgf1ag routine. The effective bandwidth was thus reduced by 13.6% to 1770 MHz. Calibrated and RFI-cleaned visibilities were finally Fourier transformed using the “robust” weighting option, varying this parameter between “natural” and “uniform” weighting and selecting the one that gave the best result, reaching an rms value of 7 $\mu$Jy at 5.5 GHz and 5 $\mu$Jy at 9.0 GHz. Flux measurements were done using the imfit task by fitting a two-dimensional Gaussian profile.

3. RESULTS

We detect the GRB host galaxy in the 5.5 GHz band with a total integrated flux density of $F_\nu = 43 \pm 11$ $\mu$Jy. The flux is nearly centered at the bulge of the galaxy. The fact that the radio emission is not exactly centered at the optical center of the bulge (offset $\sim 0.4$) could be an additional interesting feature. However, given our synthesized beam size and signal-to-noise ratio (S/N), the positional radio uncertainty is 0$'$2 (as it follows from the imfit task under MIRIAD). Moreover, the astrometric uncertainty between the radio and the optical image has similar amplitude. The 0$'$4 offset is therefore statistically not significant ($<3\sigma$). According to D’Avanzo et al. (2009), during the spectroscopic observations the slit was centered on the bulge of the galaxy with its orientation in north–south direction. The [O II] line flux reported by D’Avanzo et al. (2009) therefore traces the region where we detect the radio emission.

No emission is detected from the position of the afterglow (Figure 1), although the galaxy is resolved as an extended object: the deconvolved position angle of its radio image ($\sim 70.6 \pm 16.6$ deg) agrees within its $1\sigma$ error with the orientation of the galaxy in the optical image. The galaxy is not detected in the 9 GHz band ($F_\nu < 26$ $\mu$Jy, $3\sigma$); a limit on the spectral slope between both bands is then about $-1.0 \pm 0.5$.

To further constrain the spectral energy distribution (SED) of the galaxy, we explored the Wide-field Infrared Survey Explorer (WISE) satellite data archive (Wright et al. 2010). WISE has observed the entire sky in four bands at 3.4, 4.6, 12, and 22 $\mu$m. The catalog lists only sources with a measured S/N greater than 5 in at least one band. WISE detected the galaxy as a relatively bright source with AB magnitudes of $W1(3.4 \mu$m) = 18.27 $\pm$ 0.03, $W2(4.6 \mu$m) = 18.47 $\pm$ 0.05, $W3(12 \mu$m) = 17.13 $\pm$ 0.16, and $W4(22 \mu$m) $> 16.2$ (Figure 2). Combining these data with optical/NIR photometry from Leibler & Berger (2010),

\textsuperscript{10} http://www.narrabri.atnf.csiro.au/observing/users_guide/html/new_atug.pdf
\textsuperscript{11} http://www.atnf.csiro.au/computing/software/miriad/
we applied the SED fitting method detailed in Michałowski et al. (2008, 2009, 2010a, 2010b) based on 35,000 templates in the library of Iglesias-Páramo et al. (2007), plus some templates of Silva et al. (1998) and Michałowski et al. (2008), all developed in GRASIL (Silva et al. 1998). They are based on numerical calculations of radiative transfer within a galaxy, which is assumed to be a triaxial system with diffuse dust and dense molecular clouds, in which stars are born. The GRASIL fit results in a SFR of $\sim 24 \, M_\odot$ yr$^{-1}$, about 40 times higher compared to what was derived based on the [O II] emission line flux. The mean host extinction is $A_V \sim 2.0$ mag (see Section 4.2), a value similar to what was deduced by Leibler & Berger (2010) based on their photometry and SED fitting. The infrared data alone lead to an estimated SFR of $40 \, M_\odot$ yr$^{-1}$, while using Equation (6) in Bell (2003) the 5.5 GHz flux translates into an unobscured SFR of $\sim 30 \, M_\odot$ yr$^{-1}$. These numbers characterize the host of GRB 071227 as a galaxy that is undergoing an episode of intense star formation.

4. DISCUSSION

4.1. Is GRB 071227 a Member of the Long-burst Population?

That the host of GRB 071227 is an actively star-forming galaxy would not attract attention if the burst were a member of the long-burst population, i.e., had a collapsar origin. The short GRB 090426 (at $z = 2.609$) is a good example of a similar case in which the afterglow data strongly disfavor a merger origin. In the observer frame it had a duration of $T_\text{90} = 1.25 \pm 0.25$ s (rest frame 0.33 s). However, several arguments have been put forward that this burst was due to a collapsar event. These include the afterglow luminosity, the circumburst density, the spectral and energy properties of the GRB and the exceptionally high redshift for a short burst (e.g., Nicuesa Guelbenzu et al. 2006). There are several reasons: (1) if this event had been seen across the galactic plane of its host, then a host extinction $A_V \gtrsim 2.5$ mag could have dimmed the SN light below the detection threshold. (2) Given the observed wide spread in GRB-SN luminosities (e.g., Ferrero et al. 2006; Kann et al. 2011), a photometric detection of a SN following this event was not expected with any certainty. (3) The long GRBs 060505 and 060614 did not even have any SN signal down to hundreds of times fainter than archetypal GRB SNe (Fynbo et al. 2006).

A strong argument against a collapsar origin of GRB 071227 comes from the properties of its prompt emission. First, the spectral lag of the first, intense spike is consistent with zero (Sakamoto et al. 2007b), a feature found to be characteristic of short bursts (Norris & Bonnell 2006; Zhang et al. 2006). Second, in the Amati iso–$E_{\text{iso}}$–$E_{\text{peak}}$ diagram (Amati et al. 2008), where long and short bursts separate, the hard spike of GRB 071227 lies in the region occupied by short bursts. Caiho et al. (2010) have discussed in detail GRB 071227 and concluded that the properties of its prompt emission define the burst as a member of the short-burst population. Third, the observed extended emission of the burst (Section 1) is similar to about ten other cases of short bursts which can be understood as magnetar-powered GRBs (Gompertz et al. 2014). In addition, we also note that the luminosity of the optical afterglow of GRB 071227 (D’Avanzo et al. 2009) lies in the region occupied by short GRBs (Kann et al. 2011).

4.2. Comparison of the GRB 071227 Host Galaxy with Other Short-burst Hosts

The high SFR puts the host of GRB 071227 in line with the hosts of the short GRBs 100206A (SFR $\sim 30 \, M_\odot$ yr$^{-1}$, $z = 0.407$; Perley et al. 2012) and 120804A (SFR $\sim 300 \, M_\odot$ yr$^{-1}$, $z \sim 1.3$; Berger et al. 2013). In particular, it is the third known luminous infrared galaxy (LIRG) that hosted a short GRB. Among the 25 short-burst host galaxies compiled and listed in Berger (2013) which have a measured SFR (bursts from mid 2005 to mid 2013), 19 have a SFR $\lesssim 2.5 \, M_\odot$ yr$^{-1}$ (excluding here GRB 071227) and three others lie between 6 and 16 $M_\odot$ yr$^{-1}$.

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12 There are seven free parameters in the library of Iglesias-Páramo et al. (2007) (their Table 3): the normalization of the Schmidt-type law, the timescale of the mass infall, the intensity of the starburst, the timescale of the molecular cloud destruction, the optical depth of molecular clouds, the age of a galaxy, and the inclination of a disk with respect to the observer. Parameter ranges used are, e.g., $A_V = 0$–5.5 mag and metalliclicity from $4 \times 10^{-4}$ to 4.0 solar.

13 SN 1998bw peaked at $L_{\text{bol}} \sim 1 \times 10^{43} \, \text{erg s}^{-1}$ (Pian et al. 2006) with $M_V \sim -19.2 + 5 \log h_{\odot}$ (Galama et al. 1998).

14 The arrival time difference between high and low-energy photons.
GRB 100206A. There is only one more short-burst host that has detections in the W1, W2, and W3 bands, namely the suspected host of GRB 060502B (z = 0.287; Bloom et al. 2007), though here the GRB-host association is not nearly as secure as in the case of GRB 071227.

While a WISE detection naturally favors low-z galaxies, a comparison of long-burst hosts with galaxies hosting short bursts is worthwhile. We found that only one out of five \(z < 0.5\) long-burst host galaxies in the TOUGH host galaxy survey (Hjorth et al. 2012) has detections in W1, W2, and W3. The comparably high percentage of WISE-detected short-burst host galaxies could be indicative that a fraction may have short merger timescales.

4.3. Is the Host Galaxy of GRB 071227 an AGN?

Michałowski et al. (2008) compiled evidence that long-GRB hosts are probably not powered by active galactic nuclei (AGNs). Berger et al. (2013) discussed in detail the radio-detection of the host of the short GRB 120804A and concluded that it appears unlikely that this host harbors an AGN. And what is the status of GRB 071227?

Our radio detection at 5.5 GHz corresponds to a specific luminosity of \(L_v = 1.6 \times 10^{29} \text{ erg s}^{-1} \text{ Hz}^{-1}\). Assuming a spectral slope in the radio band of \(-0.75\), at 1.4 GHz we expect a flux density of 150 \(\mu\text{Jy}\). According to Huynh et al. (2005) and Ballantyne (2009), for such a flux density roughly 25% of sources are AGNs.

X-ray emission is one of the principal characteristics of AGN activity. As an upper limit on the X-ray flux of the GRB host galaxy we can take the non-detection of the afterglow by Swift at \(t = 314\) ks with \(F_{\gamma}(0.3–10\text{ keV}) < 1.3 \times 10^{-19} \text{ erg s}^{-1} \text{ cm}^{-2}\) (see the Swift light curve repository; Evans et al. 2007, 2009). For the given redshift this gives \(L_X < 6.5 \times 10^{42} \text{ erg s}^{-1}\), which is unfortunately not very constraining.

However, there are two reasons that make us believe that our radio detection is most likely not due to AGN activity: (1) the galaxy’s colors in the WISE diagram (Figure 3) place it significantly far from the region occupied by AGNs. (2) As stressed in Section 3, at 5.5 GHz the galaxy does not appear as a point source but is extended with the position angle oriented along the orientation of the galactic plane.

4.4. Was GRB 071227 Due to a Young Progenitor System?

Our radio observations show that GRB 071227 originated in a galaxy that is undergoing an episode of intense star formation. Also the short GRBs 100206A and 120804A were hosted in galaxies with high SFRs of \(\sim 30 \text{ M}_\odot \text{ yr}^{-1}\) (Perley et al. 2012) and \(\sim 300 \text{ M}_\odot \text{ yr}^{-1}\) (Berger et al. 2013), respectively (see also Table 1). In light of the high SFR found for the host galaxy of the short GRB 100206A, Perley et al. (2012) discussed the question whether the GRB progenitor was a member of an old or a young stellar population. In other words could it have been physically related to the recent high SFR in its host?

In the case of GRB 071227, a link between the high SFR in the bulge of its host galaxy and its position about 15 kpc (~3′) away from the galactic bulge in the galactic disk would require a (projected) kick velocity of the NS binary of about 150/f8 km s\(^{-1}\), where f8 is the age of the GRB progenitor in units of \(10^8\) yr. For f8 \(\sim 1\), the typical range in ages for starbursts traced by radio continuum observations, the required kick velocity is relatively modest when compared with the kick velocities of some Galactic NSs (e.g., Tomsick et al. 2012), and might even be small compared to NS–NS/NS–BH systems.
the other hand, whether 150 km s$^{-1}$ is a relatively high or even an unreasonable high value for a short-burst progenitor is difficult to evaluate, at least form the observational point of view. While the majority of all short bursts with well-defined host galaxies (e.g., Fong et al. 2011, 2013; Leibler & Berger 2010; Berger 2013; Fong & Berger 2013) seems to have relatively low space velocities (because they exploded close to galaxies, suggesting that these are their hosts), several apparently host-less bursts are also known (e.g., Tumlincliff et al. 2014). The latter could imply high kick velocities, even though in these cases substantial stellar ages of, say, 10 billion years, could finally relax the requirement for a high kick velocity.

Alternatively, as discussed by D’Avanzo et al. (2009), the progenitor could have been born in a star-forming region in the galactic disk and exploded (merged) within even shorter timescales of $10^7$–$10^8$ yr. This scenario avoids the need for a high kick velocity and for a kick velocity vector that lies nearly parallel to the orientation of the galactic plane. A possible causal connection to the high SFR in the central parts of the galaxy could nevertheless still exist, given that at least in the local universe LIRGs show that star-forming activity in the nuclear regions is usually spread out in a galaxy on kpc scales (Alonso-Herrero et al. 2013). Our radio observations then just pick out the radio-brightest central region of the galaxy.

5. SUMMARY AND CONCLUSIONS

We detect the host galaxy of the short GRB 071227 at 5.5 GHz with a flux density of $\sim 45 \mu$Jy, implying a SFR of about $30 M_\odot$ yr$^{-1}$. This is the second host galaxy of a short burst detected in the radio band and the third short-burst host found to be an infrared luminous galaxy. Having now found a third such case among the relatively small sample of about 30 well-studied short-burst hosts suggests that some observed stellar merger events could be physically related to recent star-forming activity. A subgroup of short-GRB progenitors could then merge within relatively short timescales, contrary to what characterizes the short-GRB progenitor population hosted by elliptical galaxies.

Similar to what has been found for the type Ia SN rate (e.g., Aubourg et al. 2008), also the short-GRB rate in a galaxy might depend on its recent SFR as well as its total mass. In fact, all three galaxies we have discussed here are found to be very massive (Table 1). More systematic surveys of the hosts of short GRBs in the radio and infrared bands are needed to address this issue.

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Figure 4. Spectral energy distribution of the three short GRB hosts with (U)LIRG SFRs after correction for Galactic extinction. Red squares are data points, whereas blue lines denote GRASIL models. For GRB 100206A and 120804A we made use of the data published in Perley et al. (2012) and Berger et al. (2013), respectively. Note that the GRASIL fit assumes a radio slope of $-0.75$. The host of GRB 071227 has a slightly steeper slope, explaining the slight discrepancy between the 9 GHz upper limit and the fit.

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