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Late Afterglow Emission Statistics: A Clear Link between GW170817 and Bright Short Gamma-Ray Bursts

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Abstract

GW170817, the first neutron star merger event detected by Advanced LIGO/Virgo detectors, was associated with the underluminous short-duration GRB 170817A. In this Letter we compare the forward shock afterglow emission of GW170817/GRB 170817A to other luminous short gamma-ray bursts (SGRBs) with both a known redshift and an afterglow emission lasting at least one day after the burst. In the rapid decay phase, the afterglow emission of the bright SGRBs and GW170817/GRB 170817A form a natural and continuous sequence, though separated by an observation time gap. If viewed on-axis, in the bursters' frames the forward shock afterglow emission of GW170817/GRB 170817A would be among the brightest detected thus far. This provides strong evidence for the GW170817-like merger origin of bright SGRBs, and suggests that the detection of the forward shock afterglow emission of most neutron star merger events are more challenging than the case of GW170817, as usually the mergers will be more distant and the viewing angles are plausibly higher.

Key words: binaries: close – gamma-ray burst: general – gravitational waves

1. Introduction

The mergers of double neutron star systems or the neutron star-black hole binaries generate strong gravitational wave (GW) radiation as well as short-duration gamma-ray bursts (SGRBs; including the so-called long-short GRBs that have a duration longer than 2 s but are unaccompanied by supernova emission down to very stringent limits; Eichler et al. 1989; Piran 2004; Della Valle et al. 2006; Fynbo et al. 2006; Berger 2014). Before 2017, it was widely believed that the GW/SGRB association rate is low because the SGRB outflows are highly collimated with a typical half-opening angle of ∼0.1 rad (Clark et al. 2015; Li et al. 2016). Surprisingly, on 2017 August 17, the gamma-ray monitor on board the *Fermi* γ-ray space telescope and *INTEGRAL* had successfully detected a weak-short GRB 170817A (Goldstein et al. 2017; Savchenko et al. 2017) that is spatially and temporally correlated with GW170817, the first neutron star merger event detected by Advanced LIGO/Virgo (Abbott et al. 2017). The GW/SGRB association has been formally established. However, considering the relatively small event distance ($D \sim 40$ Mpc), the isotropic-equivalent gamma-ray radiation energy of GRB 170817A is just $\sim 3 \times 10^{46}$ erg, which is at least 100 times dimmer than that of the typical SGRBs. An underluminous SGRB could either result from the breakout of the mildly relativistic shock from the leading edge of the merger-driven quasi-isotropic sub-relativistic ejecta (Kasliwal et al. 2017), or be the faint prompt emission of a highly structured relativistic ejecta viewed at a large polar angle (Jin et al. 2018). The puzzling fact that GRB 170817A and the long-duration GRB 980425 (at a distance of $D \sim 36$ Mpc, and that has been suggested to be the shock breakout signal; Kulkarni et al. 1998), the two close events with remarkably different progenitors, have rather similar luminosity and spectral peak energy (Wang et al. 2017), may favor the shock breakout model. It is thus unclear whether or not GW170817-like mergers are indeed the sources of the bright SGRBs. The forward shock afterglow observations of GW170817/GRB 170817A are helpful in answering such a question. Though the "early" rising X-ray and radio afterglow emission could be reproduced by a cocoon-like mildly relativistic ejecta (Kasliwal et al. 2017), the late-time afterglow data modelings strongly favor the presence of an off-axis relativistic (structured) outflow component (D'Avanzo et al. 2018; Lamb et al. 2018; Mooley et al. 2018b; Yue et al. 2018). Particularly, the off-axis relativistic outflow component at a viewing angle of $\theta_{\rm v} \sim 0.35$ rad has been convincingly identified/measured in the radio image (Mooley et al. 2018a; Ghirlanda et al. 2019). Nevertheless, a direct "observational" link between GW170817/GRB 170817A and bright SGRBs is still lacking. In this Letter, we carry out statistical studies of the SGRB afterglow data and aim to establish such a connection.

In the fireball afterglow model, the emission arises from the shock-accelerated electrons (with an energy distribution power-law index p) moving in the shock-generated magnetic fields (Piran 2004). A simplified uniform energy distribution with an abrupt energy depletion of a conical ejecta has been assumed in most studies. In reality, the energy distribution function could be more complicated and several empirical structured jet models (i.e., models where a jet with an angular structure where energy and velocity scale with the angular distance from the axis and a narrow fast and energetic core) have been proposed in the literature for both long-duration gamma-ray bursts (LGRBs; Dai & Gou 2001; Rossi et al. 2002; Berger et al. 2003; Zhang et al. 2004) and SGRBs (Jin et al. 2007; Ghirlanda et al. 2019). Usually the energy distribution is insensitive on the polar angle for $\theta \leqslant \theta_{\rm c}$ but drops rapidly outward, where $\theta_{\rm c}$ is the half-opening angle of the energetic core. The gamma-ray bursts (GRBs) viewed at the angles of $\theta_{\rm v} \leqslant \theta_{\rm c}$ are on-axis events; otherwise they are off-axis events. The afterglow emission of structured jets have been extensively calculated in the literature. If viewed off-axis, it is found that the early afterglow emission are sensitively dependent on the viewing angle θ_v (the larger θ_v, the weaker the emission), while at late times with the considerably decreased bulk Lorentz factor the viewing angle effect will be significantly suppressed (Kumar & Granot 2003; Wei & Jin 2003; Lamb & Kobayashi 2017). In particular, a quick decline (t^{-p}) phase will appear in the afterglow light curve when the bulk Lorentz factor of the ejecta drops to $\sim 1/(\theta_v + \theta_c)^{-1}$, after which the afterglow emission viewed at different θ_v are rather similar (Kumar & Granot 2003; Wei & Jin 2003; Piran 2004; Lamb & Kobayashi 2017). This conclusion holds for the off-axis uniform ejecta as well. Therefore we can "extrapolate" the very late quick-decaying X-ray and optical afterglow emission of GW170817/GRB 170817A to a "comparison" time $t_{com} \sim 2$ days (i.e., if viewed on-axis; the time is measured in the burster's frame) after the burst and then compare them to other distant SGRBs (see Fong et al. 2017 for a direct comparison of the "early" emerging forward shock emission of GW170817/GRB 170817A to the afterglow emission of other SGRBs). The choice of such a t_{com} is for two reasons. One is that at such a late time the forward shock emission is usually in the post-jet-break phase if viewed on-axis (i.e., the bulk Lorentz factor of the decelerated ejecta Γ drops below $1/\theta_c$ for $\theta_c \sim 0.1$ rad (Fong et al. 2015; Ghirlanda et al. 2016; Jin et al. 2018). Note that the energetic core of the relativistic outflow driven by GW170817 has an $\theta_c \approx 0.08$ rad (Mooley et al. 2018a; Ghirlanda et al. 2019). The other is that the afterglow light curves of some SGRBs do not cover a longer time. For the radio emission, $t_{com} \sim 10$ days is needed otherwise the typical synchrotron radiation frequency of the forward shock electrons (ν_m, which is independent of the number density of circumburst medium) is still above the observer's frequency and the flux will not drop with time quickly (Piran 2004). If the burst was born in a dense circumburst medium, then synchrotron self-absorption plays an important role in suppressing the radio emission as well. Fortunately, for the SGRBs, the medium density is usually low and the self-absorption correction is negligible.

2. The Samples

For our purpose, we select the events with both a known redshift and an afterglow emission lasting at least one day after the burst. In comparison to the LGRBs, SGRBs have smaller E_k mainly due to the shorter durations. The number density of the medium surrounding some SGRBs is also expected to be lower. That is why for most SGRBs the forward shock afterglow emission is faint and cannot be detected in the long term (Fong et al. 2015). The early optical observations were performed by various telescopes, while at late times only a few very large (∼8–10 m) ground-based telescopes and the *Hubble Space Telescope* (*HST*) are able to contribute. Our X-ray sample consists of 19 bursts. While in optical and radio bands, there are just seven and three bursts in our samples, respectively. The details of our samples and the data sources are the below. Note that GW170817/GRB 170817A is excluded in all of these samples.

The X-ray Sample. Our X-ray sample consists of 19 events. Most data were recorded by the *Swift* X-ray Telescope (XRT) and are available at http://www.swift.ac.uk/xrt_curves/ and http://www.swift.ac.uk/xrt_spectra/ (Evans et al. 2009). For some bursts of interest, there were deep *Chandra* or *XMM-Newton* detections. These bursts include GRB 050709 (Fox et al. 2005), GRB 050724 (Berger et al. 2005; Grupe et al. 2006), GRB 051221A (Soderberg et al. 2006), GRB 060505 (Ofek et al. 2007), GRB 120804A (Berger et al. 2013), GRB 130603B (Fong et al. 2014), GRB 140903A (Troja et al. 2016), and GRB 150101B (Fong et al. 2015).

The Optical Sample. The optical sample is composed of seven events. This sample is significantly smaller than the X-ray sample, likely due to the lack of deep follow-up observations in many events or the presence of serious dust extinction in some events. For instance, at $t > 0.1$ day after the burst the X-ray afterglow emission of GRB 120804A is brightest in the sample (see Figure 1) but no optical emission was detected (Berger et al. 2013). While on average SGRBs are expected to occur in a low-density medium, evidence for a few highly extinguished events has been reported in the literature. For GRB 130603B and GRB 140903A, the dust extinctions of the host galaxies are serious in the optical bands and have been corrected (Fong et al. 2014; de Ugarte Postigo et al. 2014; Troja et al. 2016). Other events are GRB 050724 (Berger et al. 2005; Malesani et al. 2007), GRB 051221A (Soderberg et al. 2006), GRB 060614 (Della Valle et al. 2006; Gal-Yam et al. 2006; Yang et al. 2015), GRB 150424A (Knust et al. 2017; Jin et al. 2018), and GRB 160821B (Jin et al. 2018). For a few bursts such as GRB 050709 and GRB 150101B, optical emission were detected at $t \geqslant 1$ day. These events, however, are excluded in the current sample because their late-time optical emission are likely dominated by the macronova/kilonova component (Jin et al. 2016; Troja et al. 2018). For the same concern, the very late time I/F814W or F160W data of GRB 060614 (for this burst the macronova identification strongly favors a neutron star merger origin though its duration is apparently long; Yang et al. 2015) and GRB 130603B are excluded. In Figure 2, the galactic extinction corrections have been made for all bursts (Schlafly & Finkbeiner 2011).

The Radio Sample. So far there are six SGRBs with detected radio emission (Fong et al. 2017). The radio emission of GRB 051221A was detected but it is likely from the reverse shock

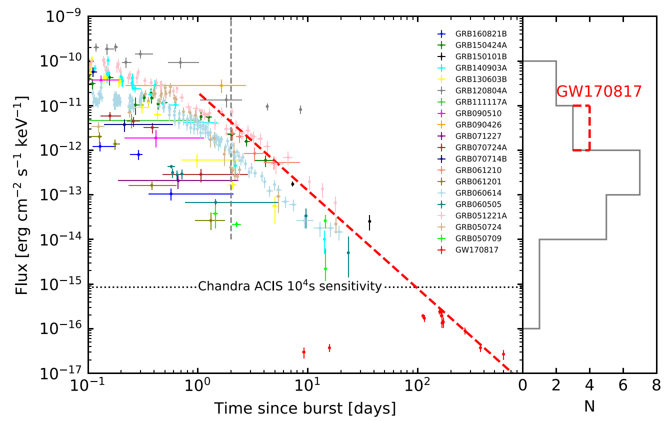

Figure 1. "Long-lasting" X-ray (1.7 keV) afterglow emission of some SGRBs and GW170817/GRB 170817A (D'Avanzo et al. 2018; Troja et al. 2018; Hajela et al. 2019), if occurring at the same distance of 200 Mpc. The red dashed line represents the "on-axis" extrapolation to early times from the very late ($t > 150$ day) X-ray afterglow data of GRB 170817A, the vertical dashed line represents the time 2 days after the burst, and the dotted horizontal line is the *Chandra* ACIS 10^4 s observation sensitivity (http://cxc.harvard.edu/cdo/about_chandra/). Please see Section 2 for the details of the X-ray sample. The right panel presents the distribution of the X-ray fluxes at a fixed time of 2 days after the burst.

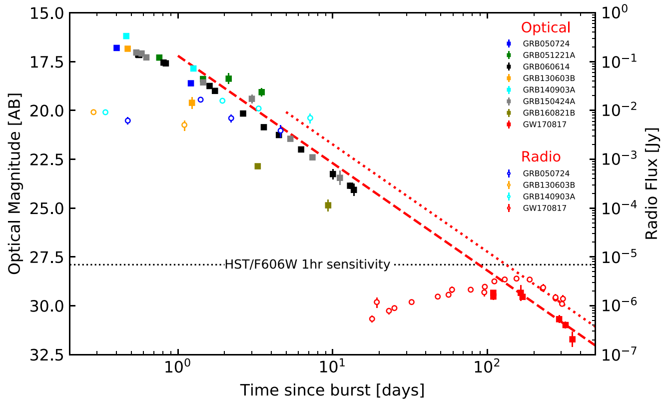

Figure 2. "Long-lasting" R-band (the filled squares) and radio (6 GHz; the open circles) afterglow emission of some SGRBs and GW170817/GRB 170817A, if taking place at the same distance of 200 Mpc. The dashed and dotted lines represent the "on-axis" extrapolation from the very late ($t > 150$ day) R-band and radio (6 GHz) afterglow data of GRB 170817A. The *HST* sensitivity is from the Wide Field Camera 3 Instrument Handbook for Cycle 27 (http://www.stsci.edu/hst/wfc3/design/at_a_glance/documents/handbooks/currentIHB/wfc3_ihb.pdf). The forward shock optical and radio afterglow data of GW170817/GRB 170817A are adopted from the literature (Lamb et al. 2018; Lyman et al. 2018; Mooley et al. 2018a, 2018b). The details of the optical and radio samples are presented in Section 2.

rather than the forward shock (Soderberg et al. 2006). GRB 150424A and GRB 160821B had been detected in radio at early times (Fong 2015; Fong et al. 2016), but they have not yet been formally published (in the GCN circulars, each event had just one data point detected at $t < 1$ day). Therefore, our radio sample just consists of GRB 050724 (Berger et al. 2005; Malesani et al. 2007), GRB 130603B (Fong et al. 2014), and GRB 140903A (Troja et al. 2016).

For two events in the above samples, there are some elements that require caution. The first is the long-short event GRB 060505; although a neutron star merger origin is possible (Ofek et al. 2007), there are also arguments in favor of a peculiar collapsar origin (Thöene et al. 2008). The second is GRB 150424A, for which redshift is not secure and may be larger than 0.7 rather than ≈0.3 (Tanvir et al. 2015). The main conclusions of this work, however, are unchanged if these two events are excluded.

3. Results and Discussion

In Figures 1 and 2 we show that the X-ray (1.7 keV[5]), optical (R-band), and radio (6 GHz) fluxes varied with the time of observation applied to the proper corrections if observed at a distance of 200 Mpc, motivated by the fact that the averaged sensitive range of the Advanced LIGO/Virgo detectors in their full-sensitivity run is about 210 Mpc, for the current samples. Due to the faintness of the SGRB afterglow emission, there are gaps of the data between the previous more distant events and GW170817/GRB 170817A (please note that for the latter we only consider the quick decline phase as the early part is significantly influenced by the beam effect of the off-axis outflow). Therefore we extrapolate the very late ($t > 200$ day) X-ray and optical afterglow data of GRB 170817A to $t \sim 2$ day after the burst and then compare them to other events. The radio to X-ray spectrum of the forward shock afterglow emission of GW170817/GRB 170817A is $f_\nu \propto \nu^{-0.6}$, which

[5] This value corresponds to the geometric mean of the XRT energy band, at which the error of the estimated flux can be reasonably suppressed.

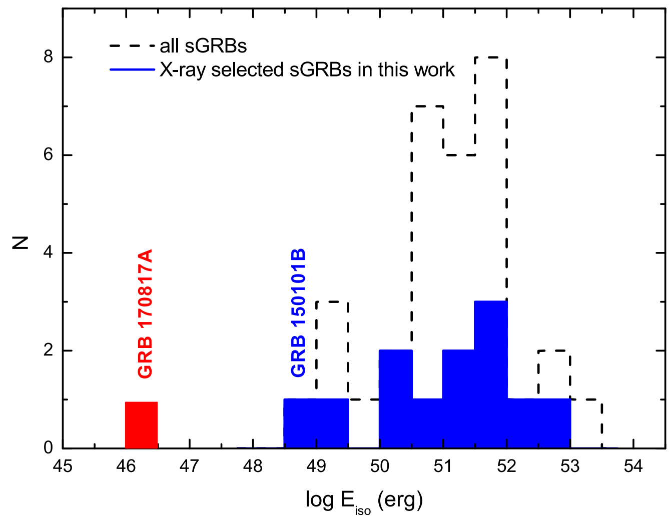

Figure 3. Distribution of the isotropic gamma-ray energy $E_{\rm iso}$ of SGRBs with a known redshift and a reliably measured spectrum. The black dashed histogram represents all current short bursts, while the red and purple shaded histograms represent the events with "long-lasting" X-ray and optical afterglow emission, respectively. GRB 170817A is marked in blue. The values of $E_{\rm iso}$ are calculated in the rest-frame energy band of 1–10^4 keV, where the redshift and spectral information of the bursts are adopted from the literature (Berger 2014; Fong et al. 2015; Lien et al. 2016; Narayana Bhat et al. 2016; Goldstein et al. 2017; Tsvetkova et al. 2017; Troja et al. 2018).

yields a $p = 2.2$ in the slow-cooling synchrotron radiation scenario (Lamb et al. 2018; Troja et al. 2018). In the jet model, such a p can also reasonably account for the very late flux decline of $f \propto t^{-2.42\pm0.2}$ (Lamb et al. 2018). The extrapolation function of the forward shock emission of GRB 170817A to early times is thus taken as $f \propto t^{-2.2}$. Surprisingly, the forward shock afterglow emission of GW170817/GRB 170817A, the first neutron star merger event detected by Advanced LIGO/Virgo, are among the brightest ones for all SGRBs detected so far. Just a few events have X-ray afterglow emission brighter than that of GRB 170817A, as demonstrated in the right panels of Figure 1. The same conclusion holds for the optical and radio afterglow data, as shown in Figure 2, though these two samples are rather limited. We have also compared the distribution of the isotropic gamma-ray energy $E_{\rm iso}$, calculated in the rest-frame energy band of 1–10^4 keV, for the SGRBs with well-measured spectra, and found no significant difference for the SGRBs with and without "long-lasting" afterglow emission (see Figure 3; where the number of events for the X-ray sample are smaller than that presented in Figure 1 because some bursts lack reliable spectral measurements). GRB170817A and GRB 150101B (Troja et al. 2018), two short events with the weakest detected prompt emission, have "bright" late-time afterglow emission because of their off-axis nature.

The above results have two intriguing implications. One is that there is a tight connection between GW170817-like mergers and the bright SGRBs, though the physical process giving rise to GRB 170817A is still yet to be understood. The other is that the detection of the forward shock afterglow emission of most (though not all) neutron star merger events is likely more challenging than in the case of GW170817, because usually the mergers will be more distant and the viewing angles will be larger (Lamb & Kobayashi 2017).

In both Figures 1 and 2, there are observation time gaps (roughly from ∼10–30 days to ∼150 days) between the sharp decline phases of the forward shock afterglow emission of GW170817/GRB 170817A and those of the much more distant events (note that the second-nearest short/long-short burst has a redshift that is about 10 times that of GRB170817A). Such gaps are expected to be bridged as some other off-axis GW/GRB events, but less extreme than GW170817/GRB 170817A (i.e., $\theta_v \gtrsim \theta_c$, which we call the quasi-on-axis events), have been discovered and closely followed. The quasi-on-axis events are less frequent than GW170817/GRB 170817A plausibly by a factor of $\sim$10, but statistically the forward shock peak time will be earlier and the afterglow emission are brighter, which can be well recorded. This would particularly be the case in X-ray and radio bands, for which the contamination by the macronova/kilonova are negligible.

With a local neutron star merger rate of $\sim 10^3$ Gpc^{-3} yr^{-1}, as inferred from both the GW data (Abbott et al. 2017) and the SGRB observations (Fong et al. 2015; Jin et al. 2018), in the era of the full-sensitivity run of the second-generation gravitational wave detectors, a sample consisting of $\sim 10^2$–10^3 neutron star mergers will be available. Some of them may generate detectable very late forward shock afterglow emission. With a reasonably large sample, the luminosity function of the quickly decaying (i.e., post-jet-break) forward shock afterglow emission driven by the neutron star mergers will be reconstructed. Intriguing differences between the double neutron star merger events and the neutron star-black hole merger events may be identified in the afterglow data. As for the double neutron star merger events, special attention may be paid to probing the possible correlations between the total mass ($M_{\rm tot}$) or the mass asymmetry (q) of the progenitor stars and the luminosity of the very late afterglow emission. GW170817 has a $M_{\rm tot} \approx 2.74 M_\odot$ ($q \approx 0.86$), which seems to be in the high total mass (high mass asymmetry) part of the double neutron star binary systems detected in the Galaxy (Huang et al. 2018), while the absence of $M_{\rm tot}$ and q of the progenitor stars for all other SGRBs hamper further progress. The situation will change drastically in the next decade, and the roles of properties of the progenitor stars on launching the relativistic outflows and generating the (very late) forward shock afterglow emission will be revealed.

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