GRB 170817A: a short GRB seen off-axis

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Abstract The angular distribution of gamma-ray burst (GRB) jets is not yet clear. The observed luminosity of GRB 170817A is the lowest among all known short GRBs, which is best explained by the fact that our line of sight is outside of the jet opening angle, \( \theta_{\text{obs}} > \theta_j \), where \( \theta_{\text{obs}} \) is the angle between our line of sight and the jet axis. As inferred by gravitational wave observations, as well as radio and X-ray afterglow modeling of GRB 170817A, it is likely that \( \theta_{\text{obs}} \sim 20^\circ \sim 28^\circ \). In this work, we quantitatively consider two scenarios of angular energy distribution of GRB ejecta: a top-hat jet and a structured jet with a power law index \( s \). For the top-hat jet model, we get a large \( \theta_j \) (e.g., \( \theta_j > 10^\circ \)), a rather high local (i.e., \( z < 0.01 \)) short GRB rate \( \sim 8 \times 10^3 \text{ Gpc}^{-3} \text{yr}^{-1} \) (estimated to be \( 90 \sim 1850 \text{ Gpc}^{-3} \text{yr}^{-1} \) in Fong et al.) and an extremely high \( E_{\text{peak,0}} \) (on-axis, rest-frame) > 7.5 \( \times 10^4 \text{ keV} \) (\( \sim 500 \text{ keV} \) for a typical short GRB). For the structured jet model, we use \( \theta_{\text{obs}} \) to give limits on \( s \) and \( \theta_j \) for typical on-axis luminosity of a short GRB (e.g., \( 10^{49} \text{ erg s}^{-1} \sim 10^{51} \text{ erg s}^{-1} \)), and a low on-axis luminosity case (e.g., \( 10^{49} \text{ erg s}^{-1} \)) gives more reasonable values of \( s \). The structured jet model is more feasible for GRB 170817A than the top-hat jet model due to the rather high local short GRB rate, and the extremely high on-axis \( E_{\text{peak,0}} \) almost rules out the top-hat jet model. GRB 170817A is likely a low on-axis luminosity GRB (\( 10^{49} \text{ erg s}^{-1} \)) with a structured jet.

Key words: short gamma-ray burst: individual (GRB 170817A) — gravitational wave

1 INTRODUCTION

Gamma-ray bursts (GRBs) are the brightest flashes of \( \gamma \)-rays, which are thought to arise from stellar-level explosions. The duration of observed \( \gamma \)-ray emission varies from tens of milliseconds to thousands of seconds. It is well known that the observed duration of GRBs has a bimodal distribution: short GRBs last \( \lesssim 2 \text{ s} \) and have harder spectra, while the duration of long GRBs is \( \gtrsim 2 \text{ s} \) and their spectra are softer (Nakar 2007). Long GRBs are due to collapse of massive stars, and so in most cases they are accompanied by observed supernovae if they are close enough, with some exceptions (e.g., Della Valle et al. 2006). Short GRBs can be produced during mergers of two compact objects, such as two neutron stars (NSs) or an NS with a black hole (Eichler et al. 1989).

Over the last three decades, nearly a thousand short GRBs have been discovered by monitoring satellites like \( \text{BATSE} \) (Fishman et al. 1994), \( \text{Swift} \) (Gehrels et al. 2004) and \( \text{Fermi} \) (Meegan et al. 2009). Before GW 170817, no gravitational wave (GW) signal had been detected from the direction of any short GRBs by LIGO/Virgo (e.g., Abbott et al. 2016). In recent years, strong evidence for mergers has been emerging, namely the detection of kilonovae or macronovae in GRB 130603B (e.g., Tanvir et al. 2013; Berger 2014), GRB 060614 (e.g., Yang et al. 2015; Jin et al. 2015) and GRB 050709 (Jin et al. 2016). Kilonovae or macronovae are powered by r-process nucleosynthesis, a process that can be triggered by NS-NS mergers (e.g., Li & Paczynski 1998; Kulkarni 2005; Hotokezaka et al. 2013). With the \( \text{Fermi} \) Gamma-ray Burst Monitor (GBM) detection of GRB 170817A after the aLIGO event GW 170817 (LIGO Scientific Collaboration & Virgo Collaboratio 2017), the
first direct evidence of an NS-NS merger origin for short GRBs has been established.

In the dawn of GW astronomy, short GRBs are one of the best electromagnetic (EM) wave counterparts of GW events (e.g. Baiotti & Rezzolla 2017; Paschalidis 2017). Since Fermi was launched in 2008, the GBM has detected more than 350 short-duration GRBs (Gruber et al. 2014). The GBM consists of 12 NaI detectors with energy range of 8 keV to 1 MeV, and two BGO detectors with energy range of 200 keV to 40 MeV. When the Fermi GBM is triggered by a GRB, the GRB location can be calculated from the 12 NaI detectors. In the current era of multi-messenger astronomy, it is predicted that more and more low-luminosity GRBs like GRB 170817A will be recorded by GRB monitors in the future including SVOM, GeCAM, etc.; many of these GRBs may be EM counterparts of GW events, and those GRBs may help us to obtain accurate GW source locations, paving the way for studying their merger environment (e.g., host galaxy types) and their progenitors. In this paper, we analyze the Fermi GBM data of GRB 170817A and compare its properties with the short GRB population. We argue that an off-axis line of sight in different jet models can quantitatively explain its low luminosity in the γ-ray band.

2 PROPERTIES AND DATA ANALYSIS OF GRB 170817A

2.1 Properties of GRB 170817A

GRB 170817A triggered the Fermi-GBM instrument at 12:41:06.475 UT on 2017 August 17 (which is defined as \( t_0 \) in this work; see Fig. 1) with a time delay of \( \sim 1.7 \) s after GW 170817 was recorded. The INTEGRAL/SPI-ACS also detected this short GRB, removing any doubt on the reliability of the GBM detection. The time duration of GRB 170817A is \( T_{90}=1.984\pm0.466 \) s in the 50–300 keV band. The GBM-determined location is RA = 176.8°, DEC = −39.8° (J2000 degree) by ground-based calculation, with an uncertainty of 11.6 degrees (1-sigma containment; von Kienlin et al. 2017). Figure 1 shows the count rate seen by the Fermi GBM detector. It can be seen that the light curve exhibits a weak and short pulse. Fermi LAT did not detect this GRB, and the angle from the Fermi LAT boresight was 91 degrees at the time that the GBM was triggered (von Kienlin et al. 2017).

2.2 Fermi GBM Spectral Analysis of GRB 170817A

We selected the data obtained by NaI (1, 2, 5) detectors whose pointing direction was within a burst angle of 60 degrees, available at the Fermi Science Support Center. We analyzed the time tagged event (TTE) data, taking advantage of its 32 ms timing resolution, with the RMFIT 43pr2 package. For spectral analysis, we used three common spectral models: power-law (PL), Comptonized model (COMP) and blackbody (BB), to fit the data. The PL model is defined as

\[
f_{\text{PL}}(E) = A \left( \frac{E}{E_{\text{piv}}} \right)^{-\alpha},
\]

where \( A \) is the normalization factor at 100 keV in units of \( \text{ph s}^{-1} \text{ cm}^{-2} \text{ keV}^{-1} \), \( \alpha \) is the spectral index and \( E_{\text{piv}} \) is fixed to 100 keV.

Some short GRBs have a thermal component from the photosphere emission which can produce BB radiation, and thermal radiation may also be expected for magnetar bursts (soft gamma-ray repeaters (SGRs)), so we also fit the spectra with the model of a BB

\[
f_{\text{BB}}(E) = A \left( \frac{E^2 dE}{kT} \right) \exp \left( \frac{E}{kT} - 1 \right),
\]

where \( A \) and \( kT \) are free parameters. Here \( A \) is the normalization factor in units of \( \text{erg cm}^{-2} \text{ s}^{-1} \) and \( kT \) is in the unit of keV. The COMP model is a useful model for short GRBs, which is represented by a power law with an exponential cutoff

\[
f_{\text{COMP}}(E) = A \left( \frac{E}{E_{\text{piv}}} \right)^{\alpha} \exp \left[ -\frac{(\alpha + 2)E}{E_{\text{peak}}} \right].
\]

The free parameters are \( A \), which is amplitude factor at 100 keV in units of \( \text{ph s}^{-1} \text{ cm}^{-2} \text{ keV}^{-1} \), \( \alpha \), which is the low-energy spectral index, and \( E_{\text{peak}} \), which is the peak energy in units of keV. \( E_{\text{piv}} \) is also fixed to 100 keV.

Using RMFIT for spectral analysis, we consider four time intervals (see Table 1 and Fig. 1). For every interval, we try the above three models to fit the data. The PL model can satisfactorily fit the spectrum in all intervals. In the first interval of \( t_0-0.128 \) s to \( t_0+0.512 \) s and the main burst interval \( t_0-0.128 \) s to \( t_0+1.984 \) s, the spectrum is better fit by the COMP model with improvement of \( \Delta \text{C-Stat} > 5 \). The results of the spectral analysis are summarized in Table 1. Our analytic result is consistent with the Fermi GBM team’s result (Goldstein et al. 2017).

Now we are ready to compare the properties of GRB 170817A with those of other short GRBs. The
Fig. 1  *Top panel:* The 7–800 keV light curve of GRB 170817A obtained by the *Fermi* NaI 2 detector with a temporal resolution of 32 ms. Periods I, II and III indicate different time ranges for spectral analysis (Sect. 2.2). *Bottom panel:* Light curves of GRB 170817A observed by the *Fermi* NaI 2 detector binned with the same temporal resolution in different energy ranges. The two *dash-dotted lines* mark the period used in the whole burst spectral analysis as shown in Table 1.

low-energy index, \( \alpha \), of GRB 170817A in the COMP model is similar to other short GRBs, cf., the average \( \alpha_{SGRB} = -0.6 \) (\( \sigma = 0.4; \) D’Avanzo et al. 2014). We compare the spectral parameters of GRB 170817A with those of GBM-detected short GRBs satisfactorily fitted by the COMP model over the \( T_{90} \) duration. To do this, we obtained the relevant COMP spectral parameters of these short GRBs (taken as \( T_{90} \leq 2\) s) from the GBM spectral catalog (Gruber et al. 2014; von Kienlin et al. 2014; Bhat et al. 2016). The results are shown in Figure 2. It can be seen that GRB 170817A still lies within the main distribution in the two figures plotting \( T_{90} \) versus \( \alpha \) or \( E_{\text{peak}} \). In contrast, in the plot showing the average energy flux versus \( T_{90} \), GRB 170817A is clearly an outlier. Its average energy flux in the COMP model is \( 0.8 \times 10^{-8} \text{erg s}^{-1} \text{cm}^{-2} \), lower than *Fermi* GBM short GRBs. Its energy fluence is \( \sim 2 \times 10^{-7} \text{erg cm}^{-2} \). From the above comparison, GRB 170817A is a low-luminosity short GRB.

3 DISCUSSION

It has been reported in the literature that GRB 170817A is located in the nearby galaxy NGC 4993, e.g., Coulter et al. (2017). The redshift of NGC 4993, and therefore GRB 170817A, is \( z \approx 0.0098 \), which corresponds to a luminosity distance of 42.5 Mpc (assuming \( H_0 = 69.6, \Omega_M = 0.286, \Omega_{\text{vac}} = 0.714 \)). Therefore, GRB 170817A is the nearest short GRB with known redshift (it is also the second nearest GRB, after GRB 980425 which lies at \( z = 0.0085 \); Galama et al. 1998).
Fig. 2 The upper-left, upper-right and lower-left panels show $T_{90}$ plotted against three spectral parameters obtained from the COMP model fits: low-energy index $\alpha$, $E_{\text{peak}}$ and average energy flux, respectively. Red points represent GBM-detected short GRBs ($T_{90} < 2.0$ s, since 2008) which can be satisfactorily fitted by the COMP model over the duration of the burst. The blue point represents GRB 170817A.

**Table 1** Model Fits of the Main Emission Episodes

<table>
<thead>
<tr>
<th>$t - T_0$ (s)</th>
<th>Model</th>
<th>$E_{\text{peak}}$ (keV)</th>
<th>$\alpha$</th>
<th>$kT$ (keV)</th>
<th>$C$-Stat/dof</th>
<th>Photon flux$^a$</th>
<th>Energy flux$^b$</th>
<th>$\Delta C$-stat</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-0.128-0.512$</td>
<td>PL</td>
<td>$-1.59\pm0.119$</td>
<td>-</td>
<td>-</td>
<td>460.3/407</td>
<td>2.16\pm0.33</td>
<td>2.99\pm0.55</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>BB</td>
<td>-</td>
<td>-</td>
<td>$30.73\pm4.48$</td>
<td>468.9/407</td>
<td>1.12\pm0.18</td>
<td>1.52\pm0.26</td>
<td>-8.6</td>
</tr>
<tr>
<td></td>
<td>COMP</td>
<td>$194.3\pm112.0$</td>
<td>$-1.01\pm0.41$</td>
<td>-</td>
<td>455.8/406</td>
<td>2.00\pm0.33</td>
<td>2.40\pm0.71</td>
<td>4.5</td>
</tr>
<tr>
<td>$0.512-1.408$</td>
<td>PL</td>
<td>$-1.98\pm0.46$</td>
<td>-</td>
<td>-</td>
<td>529.7/407</td>
<td>0.68\pm0.26</td>
<td>0.52\pm0.36</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>BB</td>
<td>-</td>
<td>-</td>
<td>$11.88\pm2.65$</td>
<td>524.1/407</td>
<td>0.73\pm0.22</td>
<td>0.41\pm0.13</td>
<td>5.6</td>
</tr>
<tr>
<td>$1.408-1.984$</td>
<td>PL</td>
<td>$-2.19\pm0.346$</td>
<td>-</td>
<td>-</td>
<td>447.6/407</td>
<td>1.45\pm0.34</td>
<td>0.86\pm0.39</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>BB</td>
<td>-</td>
<td>-</td>
<td>$10.22\pm1.77$</td>
<td>445.9/407</td>
<td>1.27\pm0.30</td>
<td>0.63\pm0.16</td>
<td>1.7</td>
</tr>
<tr>
<td>$-0.128-1.984$</td>
<td>PL</td>
<td>$-1.81\pm0.133$</td>
<td>-</td>
<td>-</td>
<td>487.5/407</td>
<td>1.32\pm0.18</td>
<td>1.29\pm0.27</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>BB</td>
<td>-</td>
<td>-</td>
<td>$12.70\pm1.23$</td>
<td>485.5/407</td>
<td>1.08\pm0.15</td>
<td>0.65\pm0.08</td>
<td>2.00</td>
</tr>
<tr>
<td></td>
<td>COMP</td>
<td>$66.06\pm15.5$</td>
<td>$-0.69\pm0.61$</td>
<td>-</td>
<td>481.6/406</td>
<td>1.24\pm0.17</td>
<td>0.80\pm0.13</td>
<td>5.9</td>
</tr>
</tbody>
</table>

Notes: $^a$ 10–1000 keV, in units of photons s$^{-1}$ cm$^{-2}$; $^b$ 10–1000 keV, in units of $\times 10^{-7}$ erg s$^{-1}$ cm$^{-2}$; PL is the power-law model, BB is the black body model and COMP is the Comptonized, $E_{\text{peak}}$ model.

As inferred from its observed energy fluence of $\approx 2 \times 10^{-7}$ erg cm$^{-2}$, the isotropic-equivalent energy in $\gamma$-rays, $E_{\text{iso},\gamma}$, can be calculated by

$$E_{\text{iso},\gamma} = \left( \frac{4\pi D_L^2 F}{1+z} \right),$$  \hspace{1cm} (4)

where $D_L$ is the luminosity distance and $F$ is the total energy fluence of GRB 170817A. Therefore, $E_{\text{iso},\gamma} \approx 4 \times 10^{46}$ erg, which is significantly lower than those of typical short GRBs (i.e., $E_{\text{iso},\gamma} \gtrsim 10^{50}$ erg). Correspondingly, GRB 170817A has a low luminosity of $L_{\text{iso},\gamma} \approx 2 \times 10^{43}$
Fig. 3 The constraint on $s$ and $\theta_{\text{obs}}$ for an off-axis structured jet model for GRB 170817A. Here the angular profile of structured jet luminosity is $L(\theta_{\text{obs}}) = L_{\text{core}}(\theta_{\text{obs}}/\theta_j)^{s}$ for off-axis observing angle $\theta_{\text{obs}} > \theta_j$. We take the values $4\pi L(\theta_{\text{obs}}) = 2 \times 10^{46}$ erg s$^{-1}$ and the $4\pi L_{\text{core}}$ is $10^{49}$ erg s$^{-1}$ to $10^{51}$ erg s$^{-1}$ for typical short GRBs. The dashed blue vertical lines are the viewing angles inferred from GW observation ($\theta_{\text{obs}} \leq 28^\circ$; Abbott et al. 2017). The dashed cyan vertical lines are the viewing angle derived from afterglow modeling of radio and X-ray observation ($20^\circ \leq \theta_{\text{obs}} \leq 40^\circ$; Margutti et al. 2017). The likely viewing angle is then plotted in the figures.

$10^{46}$ erg s$^{-1}$. Such a low luminosity is the most striking feature of GRB 170817A. For comparison, previously detected bright short GRBs typically have $L_{\text{iso},\gamma} \approx 10^{51}$ erg s$^{-1}$ (Zhang et al. 2012).

A GRB comes from a relativistic jet, but the angular energy distribution within the jet (or ejecta) is not yet known. It is well known that $L_{\text{obs}}$ strongly depends on the viewing angle, $\theta_{\text{obs}}$, and for a GRB with a given
intrinsic on-axis luminosity, $L_{\text{obs}}$ decreases with $\theta_{\text{obs}}$. From the detected GW 170817, $\theta_{\text{obs}} < 28^\circ$ is implied by LIGO data (Abbott et al. 2017). Margutti et al. (2017) infer $\theta_{\text{obs}} \sim 20^\circ - 40^\circ$ from radio and X-ray afterglow observations. Combining the results from these two papers, we focus on off-axis gamma-ray emission being $\theta_{\text{obs}} \sim 20^\circ - 28^\circ$. Next we consider two widely discussed models describing the angular distribution of energy within the GRB ejecta: a top-hat jet and a structured jet.

### 3.1 Top-hat Jet Model for GRB 170817A

In the standard fireball model, the angular energy distribution is uniform in the jet, and outside the jet, the energy is close to zero (Piran 1999). In this case, to be able to see the GRB, the line of sight must lie within the jet half-opening angle $\theta_j$, or with slight offset with the typical Lorentz factor $\Gamma$. In the off-axis jet, the peak energy $E_{\text{peak}}$ of the observed $vF_v$ spectrum varies with the observing angle $\theta_{\text{obs}}$. We can calculate the (on-axis, rest-frame) peak spectral energy $E_{\text{peak},0}$ by the observed $E_{\text{peak}}$. The peak energy $E_{\text{peak},0}$ can be estimated by (Salafia et al. 2016)

$$E_{\text{peak}}(\theta_{\text{obs}}) = \frac{E_{\text{peak},0}}{1 + \frac{\delta_\beta}{(1 + \beta_j)}} \begin{cases} \theta_{\text{obs}} \leq \theta_j \\ \theta_{\text{obs}} > \theta_j \end{cases}.$$  \hfill (6)

From analysis of the Fermi data in Section 2.2, the observed $E_{\text{peak}}$ of the $T_{90}$ duration is $\sim 66$ keV in Table 1, $z \approx 0.0098$, the Doppler factor is defined as $\delta_\beta = \Gamma^{-1} [1 - \beta \cos (\theta_{\text{obs}} - \theta_j)]^{-1}$, a typical $\Gamma \approx 200$, so the on-axis peak energy $E_{\text{peak},0}$ should be $> 7.5 \times 10^4$ keV for $\theta_{\text{obs}} \sim 20^\circ - 28^\circ$ and $\theta_j \sim 10^\circ - 14^\circ$ in the rest-frame. This $E_{\text{peak},0}$ is too large for a typical short GRB ($\sim 500$ keV) in the Fermi GBM Burst Catalog. So, the estimated $E_{\text{peak},0}$ almost rules out the top-hat jet model of GRB 170817A.

### 3.2 Structured Jet Model for GRB 170817A

It has been proposed that a structured jet may explain some long GRBs with low luminosity. The structured jet is widely discussed in those scenarios: a power-law distribution model (e.g. Rossi et al. 2002; Dai & Gou 2001), a Gaussian-type jet model (e.g. Zhang et al. 2004) and a two component jet model (e.g. Huang et al. 2004). This idea was also suggested for short GRBs (e.g. Aloy et al. 2005; Murguia-Berthier et al. 2017). It may therefore be conjectured that GRB 170817A is a typical short GRB with isotropic-equivalent luminosity $L_{\text{core}} \sim 10^{50}$ erg s$^{-1} - 10^{51}$ erg s$^{-1}$ inside the jet core (i.e., within a half opening angle $\theta_j$), but our line of sight is out of $\theta_j$. In the structured jet model, the energy does not sharply decrease to zero outside the jet core, but can instead follow a power-law decrease. In this case, the jet luminosity per solid angle along the direction of $\theta_{\text{obs}}$ is described by $L_{\text{obs}}(\theta_{\text{obs}}) = L_{\text{core}}(\theta_{\text{obs}} = \theta_j)^{-s}$ for $\theta_{\text{obs}} > \theta_j$ (Pescalli et al. 2015), such that the angular dependence of the energy distribution outside $\theta_j$ is described by the power law index, $s$. Different values of $s$ have been acquired through either simulations or observations, and can range from 2 to 8 (e.g., Frail et al. 2001; Pescalli et al. 2015; Kathergamaraju et al. 2018).

Here, we assume that the core luminosity in the jet $L_{\text{core}}$ is $10^{49}$ erg s$^{-1} - 10^{51}$ erg s$^{-1}$. Figure 3 shows the schematic relation between $s$ and $\theta_{\text{obs}}$ for GRB 170817A, taking representative values of $\theta_j$: $1^\circ$, $3^\circ$, $6^\circ$, $10^\circ$ and $15^\circ$. This figure can apply to future short GRBs.
with similar observed $\gamma$-ray luminosity with different $\theta_{\text{obs}}$. For GRB 170817A, we have $\theta_{\text{obs}} \sim 20^0 \sim 28^0$. In the following, we discuss the correlation between $s$ and $\theta_j$ for two typical values of on-axis $L_{\text{iso},\gamma}$:

1. If GRB 170817A is a typical bright short GRB with on-axis $L_{\text{iso},\gamma} \sim 10^{51}$ erg s$^{-1}$, the half-opening angle $\theta_j$ is constrained to be $<10^0$ for $s < 10$, and we can rule out $s < 2$ for all $\theta_j > 1^0$. If GRB 170817A has $\theta_j = 6^0$ (cf. Jin et al. 2017), then $s$ should be larger than 7, which is very large. Therefore, an on-axis luminosity of $L_{\text{iso},\gamma} \sim 10^{51}$ erg s$^{-1}$ is not preferred for GRB 170817A.

2. If GRB 170817A is a short GRB with on-axis $L_{\text{iso},\gamma} \sim 10^{49}$ erg s$^{-1}$, then $\theta_{\text{obs}} \sim 20^0 \sim 28^0$ can be satisfied with $\theta_j$ up to $15^0$ for $s < 10$. On the other hand, the constraints for $s$ are not severe ($3 < s < 9$) for $\theta_j = 3^0 \sim 10^0$. Therefore, we conclude that $\theta_j$ should be small ($\lesssim 15^0$) for $s < 10$, which is not a severe constraint.

Therefore, a low on-axis gamma-ray luminosity ($L_{\text{iso},\gamma} \sim 10^{49}$ erg s$^{-1}$) is preferred for GRB 170817A in the context of the structured jet model.

3.3 Comparison with Other Low-luminosity GRBs

Another related phenomenon is low-luminosity GRBs (llGRBs; e.g., Liang et al. 2007; Nakar 2015) which include GRB 060218 and GRB 980425. They have gamma-ray luminosity smaller than typical long GRBs (i.e., $<10^{48}$ erg s$^{-1}$). However, their gamma-ray emission properties are different from those of GRB 170817A. Even compared to conventional long GRBs, llGRBs are longer ($\sim 1000 \text{ s}$) and softer ($E_{\text{peak}} < 100 \text{ keV}$). The real nature of llGRBs is still unclear, but they are thought to arise from the same progenitors as long GRBs and are associated with broad-line Type Ic SNe. Only a handful of llGRBs are known, but from the observed rate, they outnumber long GRBs in the local Universe by about an order of magnitude. There is also evidence that the beaming factor of llGRBs is larger than that of long GRBs, so llGRBs are less collimated. A similar situation may apply to GRB 170817A: although this is the first known low-luminosity short GRB (regardless of whether this class is intrinsically less luminous or seen off-axis), the true rate might be much higher than short GRBs having more typical luminosity (e.g., $L > 10^{50}$ erg s$^{-1}$).

3.4 Low Luminosity Events – Burst of a Soft Gamma-ray Repeater

Another proposed low luminosity event is SGRs in the local Universe. These extragalactic giant SGR flares from young magnetars with a long recurrence timescale may mimic a small portion of short GRBs, as was discussed in several cases (Abbott et al. 2008; Ofek et al. 2008; Hurley et al. 2010; Abadie et al. 2012). The peak luminosity of SGR giant flares ranges from $10^{44}$ to $10^{47}$ erg s$^{-1}$. Considering the energetics of GRB 170817A, its low luminosity and $E_{\text{iso},\gamma}$ are consistent with such events. However, a major uncertainty is whether a magnetar exists after the merger of the two NSs. The duration of GRB 170817A ($\sim 2 \text{ s}$) is a bit longer than previously seen SGR flares, but the current sample of SGR giant flare light curves is still too small to exclude such a possibility.

4 SUMMARY

GRB 170817A is the closest short GRB ever known. The isotropic-equivalent energy, $E_{\text{iso},\gamma}$, of GRB 170817A is very low (i.e., its $E_{\text{iso},\gamma}$ is only $4 \times 10^{46}$ erg), which is 3–4 orders of magnitude lower than that of other short GRBs. In our paper, we analyze the GBM data of GRB 170817A, and we confirm that GRB 170817A is a typical short GRB but with low observed gamma-ray luminosity, consistent with most papers in the literature.

Inferred from GW data and radio-to-X-ray afterglow modeling, we take $\theta_{\text{obs}}$ to be $\sim 20^0 \sim 28^0$. We then compare the top-hat jet model and the structured jet model. According to our analysis, we find that a structured jet model (e.g., Aloy et al. 2005; Murguia-Berthier et al. 2017; Kathirgamaraju et al. 2018) is a more feasible model for GRB 170817A than a top-hat jet model. For a structured jet model, $\theta_{\text{obs}}$ can give a strong limit on $s$ and $\theta_j$ for a typical GRB. If GRB 170817A is a weak source, the structured jet model can fit the observation (the $\theta_{\text{obs}}$ and the low observed luminosity) with reasonable $\theta_j$ and index $s$ (e.g. $2 \sim 8$). For the top-hat jet model, it also can fit observations (i.e., the large $\theta_{\text{obs}}$ and the low observed luminosity) with a large $\theta_j$ (e.g., $\theta_j > 10^0$), but a rather high local (i.e., $z < 0.01$) short GRB rate ($> 8.1 \times 10^3$) remains a problem for the top-hat model, when compared to the estimated rate ($90 \sim 1850 \text{ Gpc}^{-3} \text{ yr}^{-1}$) in Fong et al. (2015) from a number of short GRBs. Another big challenge for the top-hat jet model is the estimated $E_{\text{peak},0}$ ($> 7.5 \times 10^4 \text{ keV}$) of GRB 170817A, which is too
large for a typical short GRB (~ 500 keV). The estimated $E_{\text{peak},0}$ almost rules out the top-hat jet model. So, we conclude that GRB 170817A is more likely an intrinsically low luminosity GRB ($10^{49}$ erg s$^{-1}$) with a structured jet. More observations can provide further information about the jet energy distribution of similar low-luminosity short GRBs.

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