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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, $\theta_{\rm obs} > \theta_j$, where $\theta_{\rm obs}$ 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 $\theta_{\rm obs} \sim 20° – 28°$. 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 θ_j (e.g., θ_j>10°), a rather high local (i.e., $z < 0.01$) short GRB rate $\sim$8–15$\times10^3\,{\rm Gpc^{-3}\,yr^{-1}}$ (estimated to be 90$\sim$1850 ${\rm Gpc^{-3}\,yr^{-1}}$ in Fong et al.) and an extremely high $E_{\rm peak,0}$ (on-axis, rest-frame)>7.5×10^4 keV ($\sim$500 keV for a typical short GRB). For the structured jet model, we use $\theta_{\rm obs}$ to give limits on s and θ_j for typical on-axis luminosity of a short GRB (e.g., $10^{49}\,{\rm erg\,s^{-1}}\sim10^{51}\,{\rm erg\,s^{-1}}$), and a low on-axis luminosity case (e.g., $10^{49}\,{\rm erg\,s^{-1}}$) 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 $E_{\rm peak,0}$ almost rules out the top-hat jet model. GRB 170817A is likely a low on-axis luminosity GRB ($10^{49}\,{\rm erg\,s^{-1}}$) 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 γ-rays, which are thought to arise from stellar-level explosions. The duration of observed γ-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 $\lesssim 2$ s and have harder spectra, while the duration of long GRBs is $\gtrsim$2 s and their spectra are softer (Nakar 2007)[1]. 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 *BATSE* (Fishman et al. 1994), *Swift* (Gehrels et al. 2004) and *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 & Paczyński 1998; Kulkarni 2005; Hotokezaka et al. 2013). With the *Fermi* Gamma-ray Burst Monitor (GBM) detection of GRB 170817A after the aLIGO event GW 170817 (LIGO Scientific Collaboration & Virgo Collaboratio 2017), the

[1] However, there is no clear cut in duration that separates the two classes: there are short GRBs having a duration >2 s and vice versa.

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 ~ 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±0.466 s in the 50–300 keV band[2]. 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

$$f_{\rm PL}(E) = A\Big(\frac{E}{E_{\rm piv}}\Big)^{-\alpha}, \quad (1)$$

where A is the normalization factor at 100 keV in units of ph s^{-1} cm^{-2} keV^{-1}, α is the spectral index and $E_{\rm piv}$ 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

$$f_{\rm BB}(E) = A\frac{E^2 dE}{(kT)^4 \exp(E/kT) - 1}, \quad (2)$$

where A and kT are free parameters. Here A is the normalization factor in units of erg cm^{-2} 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

$$f_{\rm COMP}(E) = A\Big(\frac{E}{E_{\rm piv}}\Big)^{\alpha} \exp\left[-\frac{(\alpha+2)E}{E_{\rm peak}}\right]. \quad (3)$$

The free parameters are A, which is amplitude factor at 100 keV in units of ph s^{-1} cm^{-2} keV^{-1}, α, which is the low-energy spectral index, and $E_{\rm peak}$, which is the peak energy in units of keV. $E_{\rm piv}$ 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 ΔC-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

[2] From the *Fermi* GBM Burst Catalog, the online version is available at *https://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigbrst.html*, Gruber et al. 2014; von Kienlin et al. 2014; Bhat et al. 2016.

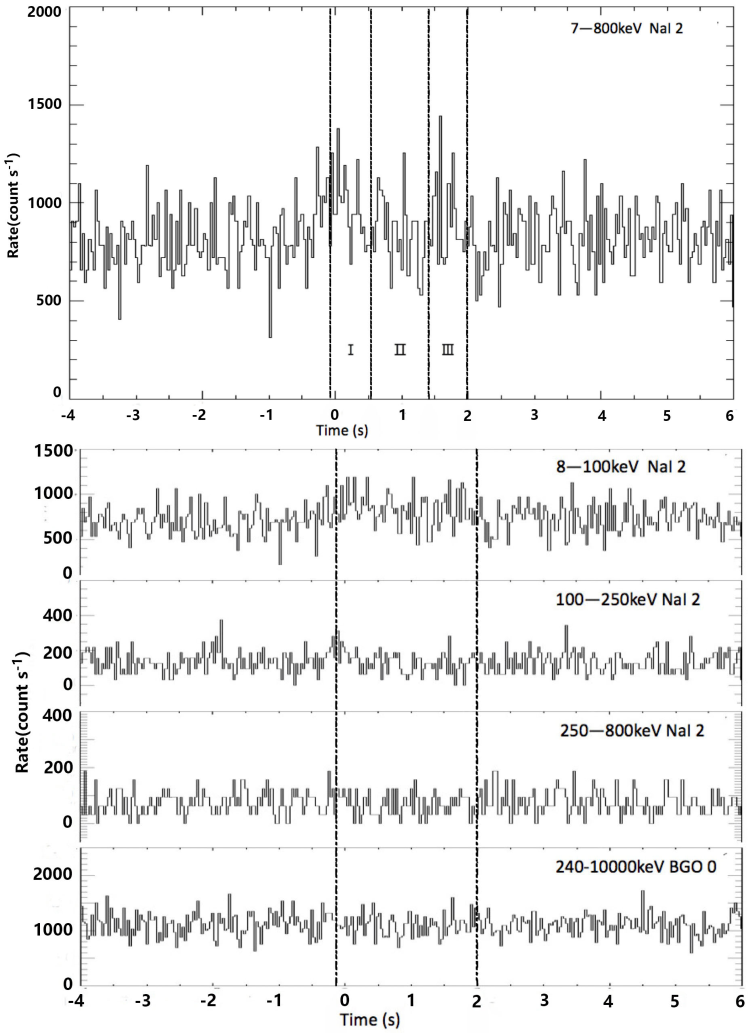

Fig. 1 *Top panel:* The 7–800 keV light curve of GRB 170817A obtained by the *Fermi* NaI 2 detector with a temporal resolution of 32 ms. Periods I, II and III indicate different time ranges for spectral analysis (Sect. 2.2). *Bottom panel:* Light curves of GRB 170817A observed by the *Fermi* NaI 2 detector 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, α, of GRB 170817A in the COMP model is similar to other short GRBs, cf., the average $\alpha_{\rm SGRB} = -0.6$ (σ = 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 α or $E_{\rm peak}$. 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 0.8×10^{-8}erg s^{-1} cm^{-2}, lower than *Fermi* GBM short GRBs. Its energy fluence is $\sim2\times10^{-7}$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, $\Omega_{\rm M}$=0.286, $\Omega_{\rm vac}$=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).

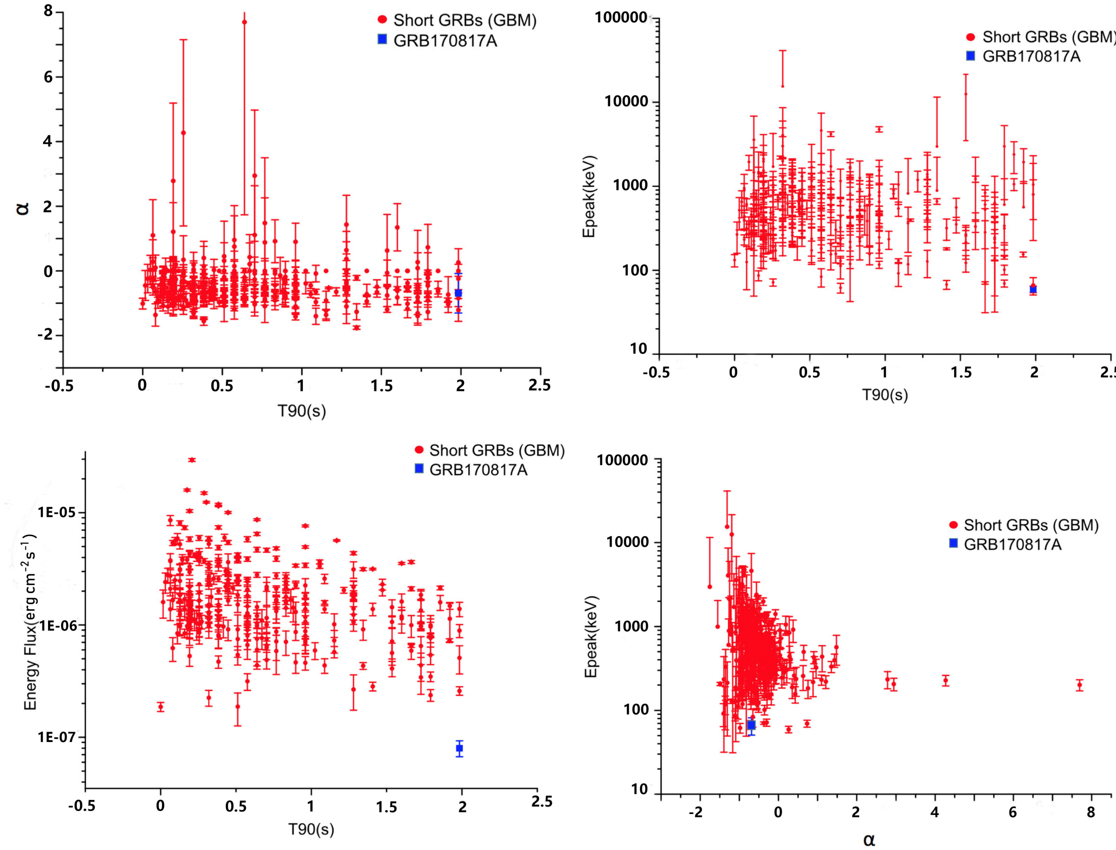

Fig. 2 The *upper-left*, *upper-right* and *lower-left* panels show T_{90} plotted against three spectral parameters obtained from the COMP model fits: low-energy index α, $E_{\rm peak}$ and average energy flux, respectively. *Red points* represent GBM-detected short GRBs (T_{90}<2.0 s, since 2008) which 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

$t - T_0$ (s)	Model	$E_{\rm peak}$ (keV)	α	kT (keV)	C-Stat/dof	photon flux^a	energy flux^b	Δc-stat
−0.128–0.512	PL	–	−1.59±0.119	–	460.3/407	2.16±0.33	2.99±0.55	–
	BB	–	–	30.73±4.48	468.9/407	1.12±0.18	1.52±0.26	−8.6
	COMP	194.3± 112.0	−1.01±0.41	–	455.8/406	2.00±0.33	2.40±0.71	4.5
0.512–1.408	PL	–	−1.98±0.46	–	529.7/407	0.68±0.26	0.52±0.36	–
	BB	–	–	11.88±2.65	524.1/407	0.73±0.22	0.41±0.13	5.6
1.408–1.984	PL	–	−2.19±0.346	–	447.6/407	1.45±0.34	0.86±0.39	–
	BB	–	–	10.22±1.77	445.9/407	1.27±0.30	0.63±0.16	1.7
−0.128–1.984	PL	–	−1.81±0.133	–	487.5/407	1.32±0.18	1.29±0.27	–
	BB	–	–	12.70±1.23	485.5/407	1.08±0.15	0.65±0.08	2.00
	COMP	66.06± 15.5	−0.69±0.61	–	481.6/406	1.24±0.17	0.80±0.13	5.9

Notes: ^{a} 10–1000 keV, in units of photons s^{-1} cm^{-2}; ^{b} 10–1000 keV, in units of $\times10^{-7}$ erg s^{-1} cm^{-2}; PL is the power-law model, BB is the black body model and COMP is the Comptonized, Epeak model.

As inferred from its observed energy fluence of $\approx 2\times10^{-7}$ erg cm^{-2}, the isotropic-equivalent energy in γ-rays, $E_{\rm iso,\gamma}$, can be calculated by

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

where D_L is the luminosity distance and F is the total energy fluence of GRB 170817A. Therefore, $E_{\rm iso,\gamma} \approx 4\times10^{46}$ erg, which is significantly lower than those of typical short GRBs (i.e., $E_{\rm iso,\gamma} \gtrsim 10^{50}$ erg). Correspondingly, GRB 170817A has a low luminosity of $L_{\rm iso,\gamma} \approx 2\times$

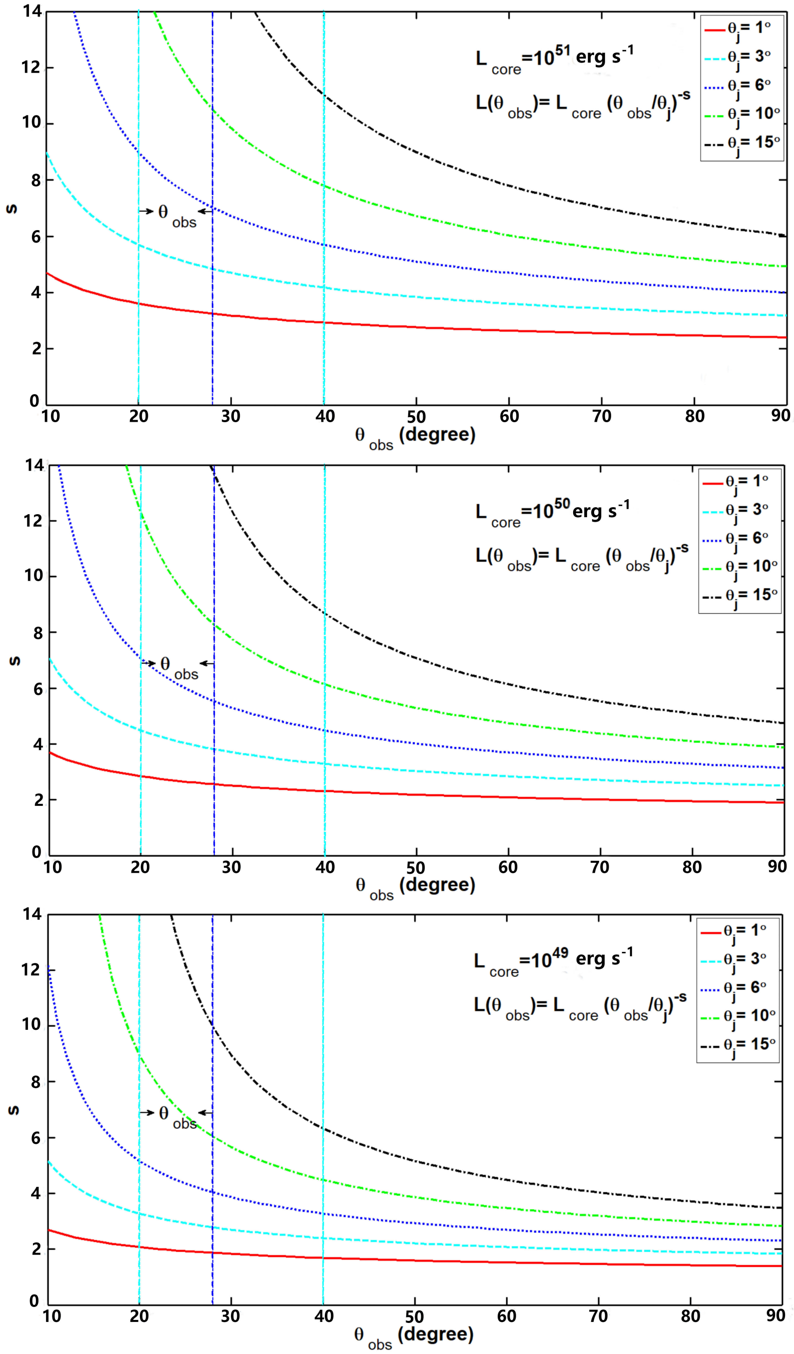

Fig. 3 The constraint on s and $\theta_{\rm obs}$ for an off-axis structured jet model for GRB 170817A. Here the angular profile of structured jet luminosity is $L(\theta_{\rm obs}) = L_{\rm core}(\theta_{\rm obs}/\theta_j)^{-s}$ for off-axis observing angle $\theta_{\rm obs} > \theta_j$. We take the values $4\pi L(\theta_{\rm obs}) = 2 \times 10^{46}$ erg s^{-1} and the $4\pi L_{\rm core}$ 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 ($\theta_{\rm obs} \leq 28^\circ$; Abbott et al. 2017). The *dashed cyan vertical lines* are the viewing angle derived from afterglow modeling of radio and X-ray observation ($20^\circ \leq \theta_{\rm obs} \leq 40^\circ$; 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 $L_{{\rm iso},\gamma} \approx 10^{51}$ 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 $L_{\rm obs}$ strongly depends on the viewing angle, $\theta_{\rm obs}$, and for a GRB with a given intrinsic on-axis luminosity, $L_{\rm obs}$ decreases with $\theta_{\rm obs}$. From the detected GW 170817, $\theta_{\rm obs} < 28^\circ$ is implied by LIGO data (Abbott et al. 2017). Margutti et al. (2017) infer $\theta_{\rm obs} \sim 20^\circ$ – 40° from radio and X-ray afterglow observations. Combining the results from these two papers, we focus on off-axis gamma-ray emission being $\theta_{\rm obs} \sim 20^\circ$ – 28°. 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 θ_j, or with slight offset with the typical Lorentz factor ~ 200 at the prompt phase (Salafia et al. 2015). For a GRB with a typical on-axis luminosity, say $10^{51}\,{\rm erg\,s^{-1}}$, with observed luminosity (to our line of sight) as low as $L_{\rm obs} \approx 10^{46}\,{\rm erg\,s^{-1}}$, $\theta_{\rm obs}$ should be about $\sim 2\theta_j$ (see Fig. 3, Salafia et al. 2015) with a typical Lorentz factor of 200. Applying this to the case of GRB 170817A, the observed angle should be $\theta_{\rm obs} \approx 2\theta_j$. Considering that $\theta_{\rm obs} \sim 20^\circ$ – 28°, we have $\theta_j \sim 10^\circ$ – 14° with a typical Lorentz factor. This means that the jet half-opening angle θ_j is consistent with what was previously inferred for short GRBs (e.g., $\sim$16°; Fong et al. 2015; though there are lower estimates, see Jin et al. 2017).

Taking the above values, the local ($z \leq$0.01) rate of short GRBs can be estimated by

$$R_{\rm nus} = \left(\frac{N_{\rm event}}{V(z\leq 0.01)T}\right)\left(\frac{4\pi}{\rm FoV}\right)\left(\frac{1}{1-\cos(2\theta_j)}\right), \quad (5)$$

where $N_{\rm event}$ is the total number of short GRBs detected within the comoving volume V ($z \leq$0.01) and the observation time span T. The *Fermi* GBM was launched in 2008, thus we take $T = 4.5\,{\rm yr}$ (taking fractional effective exposure to be 0.5), and it has a field of view (FoV) $\approx 9.5\,{\rm sr}$. Currently, GRB 170817A is the only detected GBM burst with known $z \leq 0.01$, and we have $N_{\rm event} = 1$. Therefore $R_{\rm nus}$ is $\approx 1.5\times 10^4\ {\rm Gpc^{-3}\,yr^{-1}}$ for $\theta_{\rm obs} \sim 20^\circ$, $\theta_j \sim 10^\circ$ and $\approx 8.1 \times 10^3\ {\rm Gpc^{-3}\,yr^{-1}}$ for $\theta_{\rm obs} \sim 28^\circ$, $\theta_j \sim 14^\circ$ in the local Universe ($z \leq 0.01$). This is at the high end of the estimate given in Fong et al. (2015; 90$\sim$1850 ${\rm Gpc^{-3}\,yr^{-1}}$). Such a high event rate of local short GRBs may be problematic for the top-hat jet model.

In the off-axis jet, the peak energy $E_{\rm peak}$ of the observed vF_v spectrum varies with the observing angle $\theta_{\rm obs}$. We can calculate the (on-axis, rest-frame) peak spectral energy $E_{\rm peak,0}$ by the observed $E_{\rm peak}$. The peak energy $E_{\rm peak,0}$ can be estimated by (Salafia et al. 2016)

$$E_{\rm peak}(\theta_{\rm obs}) = \frac{E_{\rm peak,0}}{1+z} \times \begin{cases} 1 & \theta_{\rm obs} \leq \theta_j \\ \frac{\delta_B}{(1+\beta)\Gamma} & \theta_{\rm obs} > \theta_j \end{cases} . \quad (6)$$

From analysis of the *Fermi* data in Section 2.2, the observed $E_{\rm peak}$ of the T_{90} duration is $\approx 66\,{\rm keV}$ in Table 1, $z \approx 0.0098$, the Doppler factor is defined as $\delta_{\rm B} = \Gamma^{-1}\left[1-\beta\cos\left(\theta_{\rm obs}-\theta_j\right)\right]^{-1}$, a typical $\Gamma \approx 200$, so the on-axis peak energy $E_{\rm peak,0}$ should be $>7.5\times 10^4\,{\rm keV}$ for $\theta_{\rm obs} \sim 20^\circ$–$28^\circ$ and $\theta_j \sim 10^\circ$–14° in the rest-frame. This $E_{\rm peak,0}$ is too large for a typical short GRB ($\sim 500\,{\rm keV}$) in the *Fermi* GBM Burst Catalog. So, the estimated $E_{\rm peak,0}$ 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 $L_{\rm core} \sim 10^{49}\,{\rm erg\,s^{-1}} - 10^{51}\,{\rm erg\,s^{-1}}$ inside the jet core (i.e., within a half opening angle θ_j), but our line of sight is out of θ_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 $\theta_{\rm obs}$ is described by $L_{\rm obs}(\theta_{\rm obs})$=$L_{\rm core}(\theta_{\rm obs}\ /\ \theta_j)^{-s}$ for $\theta_{\rm obs} > \theta_j$ (Pescalli et al. 2015), such that the angular dependence of the energy distribution outside θ_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; Kathirgamaraju et al. 2018).

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

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

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

Therefore, a low on-axis gamma-ray luminosity ($L_{\rm iso,\gamma} \sim 10^{49}\,{\rm erg\,s^{-1}}$) 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., $<10^{48}\,{\rm erg\,s^{-1}}$). However, their gamma-ray emission properties are different from those of GRB 170817A. Even compared to conventional long GRBs, llGRBs are longer ($\sim$1000 s) and softer ($E_{\rm peak}$ <100 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 $10^{47}\,{\rm erg\,s^{-1}}$. Considering the energetics of GRB 170817A, its low luminosity and $E_{\rm iso,\gamma}$ 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 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, $E_{\rm iso,\gamma}$, of GRB 170817A is very low (i.e., its $E_{\rm iso,\gamma}$ is only 4×10^{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 $\theta_{\rm obs}$ to be $\sim 20^\circ - 28^\circ$. 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, $\theta_{\rm obs}$ can give a strong limit on s and θ_j for a typical GRB. If GRB 170817A is a weak source, the structured jet model can fit the observation (the $\theta_{\rm obs}$ and the low observed luminosity) with reasonable θ_j and index s (e.g. 2 $\sim$ 8). For the top-hat jet model, it also can fit observations (i.e., the large $\theta_{\rm obs}$ and the low observed luminosity) with a large θ_j (e.g., θ_j>10°), but a rather high local (i.e., $z < 0.01$) short GRB rate ($>8.1\times10^3$) remains a problem for the top-hat model, when compared to the estimated rate (90$\sim$1850 ${\rm Gpc^{-3}\,yr^{-1}}$) in Fong et al. (2015) from a number of short GRBs. Another big challenge for the top-hat jet model is the estimated $E_{\rm peak,0}$ ($>7.5\times10^4$ keV) of GRB 170817A, which is too large for a typical short GRB ($\sim 500\,\mathrm{keV}$). The estimated $E_{\rm peak,0}$ almost rules out the top-hat jet model. So, we conclude that GRB 170817A is more likely an intrinsically low luminosity GRB ($10^{49}\,\mathrm{erg\,s^{-1}}$) 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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References

Abadie, J., Abbott, B. P., Abbott, T. D., et al. 2012, ApJ, 755, 2
Abbott, B., Abbott, R., Adhikari, R., et al. 2008, ApJ, 681, 1419
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016, Physical Review Letters, 116, 241103
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017, ApJ, 848, L12
Aloy, M. A., Janka, H.-T., & Müller, E. 2005, A&A, 436, 273
Baiotti, L., & Rezzolla, L. 2017, Reports on Progress in Physics, 80, 096901
Berger, E. 2014, ARA&A, 52, 43
Bhat, P. N., Meegan, C. A., von Kienlin, A., et al. 2016, ApJS, 223, 28
Coulter, D. A., Foley, R. J., Kilpatrick, C. D., et al. 2017, Science, 358, 1556
Dai, Z. G., & Gou, L. J. 2001, ApJ, 552, 72
D'Avanzo, P., Salvaterra, R., Bernardini, M. G., et al. 2014, MNRAS, 442, 2342
Della Valle, M., Chincarini, G., Panagia, N., et al. 2006, Nature, 444, 1050
Eichler, D., Livio, M., Piran, T., & Schramm, D. N. 1989, Nature, 340, 126
Fishman, G. J., Meegan, C. A., Wilson, R. B., et al. 1994, ApJS, 92, 229
Fong, W., Berger, E., Margutti, R., & Zauderer, B. A. 2015, ApJ, 815, 102
Frail, D. A., Kulkarni, S. R., Sari, R., et al. 2001, ApJ, 562, L55
Galama, T. J., Vreeswijk, P. M., van Paradijs, J., et al. 1998, Nature, 395, 670
Gehrels, N., Chincarini, G., Giommi, P., et al. 2004, ApJ, 611, 1005
Goldstein, A., Veres, P., Burns, E., et al. 2017, ApJ, 848, L14
Gruber, D., Goldstein, A., Weller von Ahlefeld, V., et al. 2014, ApJS, 211, 12
Hotokezaka, K., Kyutoku, K., Tanaka, M., et al. 2013, ApJ, 778, L16
Huang, Y. F., Wu, X. F., Dai, Z. G., Ma, H. T., & Lu, T. 2004, ApJ, 605, 300
Hurley, K., Rowlinson, A., Bellm, E., et al. 2010, MNRAS, 403, 342
Jin, Z.-P., Li, X., Cano, Z., et al. 2015, ApJ, 811, L22
Jin, Z.-P., Hotokezaka, K., Li, X., et al. 2016, Nature Communications, 7, 12898
Jin, Z.-P., Li, X., Wang, H., et al. 2017, arXiv:1708.07008
Kathirgamaraju, A., Barniol Duran, R., & Giannios, D. 2018, MNRAS, 473, L121
Kulkarni, S. R. 2005, astro-ph/0510256
Li, L.-X., & Paczyński, B. 1998, ApJ, 507, L59
Liang, E., Zhang, B., Virgili, F., & Dai, Z. G. 2007, ApJ, 662, 1111
LIGO Scientific Collaboration & Virgo Collaboration 2017, GCN, 21509
Margutti, R., Berger, E., Fong, W., et al. 2017, ApJ, 848, L20
Meegan, C., Lichti, G., Bhat, P. N., et al. 2009, ApJ, 702, 791
Murguia-Berthier, A., Ramirez-Ruiz, E., Montes, G., et al. 2017, ApJ, 835, L34
Nakar, E. 2007, Phys. Rep., 442, 166
Nakar, E. 2015, ApJ, 807, 172
Ofek, E. O., Muno, M., Quimby, R., et al. 2008, ApJ, 681, 1464
Paschalidis, V. 2017, Classical and Quantum Gravity, 34, 084002
Pescalli, A., Ghirlanda, G., Salafia, O. S., et al. 2015, MNRAS, 447, 1911
Piran, T. 1999, Phys. Rep., 314, 575
Rossi, E., Lazzati, D., & Rees, M. J. 2002, MNRAS, 332, 945
Salafia, O. S., Ghisellini, G., Pescalli, A., Ghirlanda, G., & Nappo, F. 2015, MNRAS, 450, 3549
Salafia, O. S., Ghisellini, G., Pescalli, A., Ghirlanda, G., & Nappo, F. 2016, MNRAS, 461, 3607
Savchenko, V., Ferrigno, C., Mereghetti, S., et al. 2016, ApJ, 820, L36
Tanvir, N. R., Levan, A. J., Fruchter, A. S., et al. 2013, Nature, 500, 547
von Kienlin A., Meegan C., Goldstein A. et al. 2017, GCN Circ. 21520
von Kienlin A., Meegan C. A., Paciesas W. S. et al. 2014, ApJS, 211, 13
Yang, B., Jin, Z.-P., Li, X., et al. 2015, Nature Communications, 6, 7323
Zhang, B., Dai, X., Lloyd-Ronning, N. M., & Mészáros, P. 2004, ApJ, 601, L119
Zhang, F.-W., Shao, L., Yan, J.-Z., & Wei, D.-M. 2012, ApJ, 750, 88