The Formation Rate of Short Gamma-Ray Bursts and Gravitational Waves

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Abstract

In this paper, we study the luminosity function and formation rate of short gamma-ray bursts (sGRBs). First, we derive the $E_p$-$L_p$ correlation using 16 sGRBs with redshift measurements and determine the pseudo redshifts of 284 Fermi sGRBs. Then, we use the Lynden-Bell $c^-$ method to study the luminosity function and formation rate of sGRBs without any assumptions. A strong evolution of luminosity $L(z) \propto (1 + z)^{4.47}$ is found. After removing this evolution, the luminosity function is $\psi(L) \propto L^{-0.29\pm0.01}$ for dim sGRBs and $\psi(L) \propto L^{-1.07\pm0.01}$ for bright sGRBs, with the break point $8.26 \times 10^{50}$ erg s$^{-1}$. We also find that the formation rate decreases rapidly at $z < 1.0$, which is different from previous works. The local formation rate of sGRBs is $7.53$ events Gpc$^{-3}$ yr$^{-1}$. Considering the beaming effect, the local formation rate of sGRBs including off-axis sGRBs is $203.31^{+1152.09}_{-39.54}$ events Gpc$^{-3}$ yr$^{-1}$. We also estimate that the event rate of sGRBs detected by the advanced LIGO and Virgo is $0.85^{+4.82}_{-0.36}$ events yr$^{-1}$ for an NS–NS binary.

**Key words:** gamma-ray burst; general – gravitational waves

**Supporting material:** machine-readable table

1. Introduction

Gamma-ray bursts (GRBs) are the most violent explosions in the universe (Berger 2014; Kumar & Zhang 2015; Wang et al. 2015). They can be divided into two groups, short GRBs (sGRBs) and long GRBs, with a separation at about 2 s (Kouveliotou et al. 1993). The uniform distribution on the sky, the log $N$–log $S$ correlation, and the discovery of the afterglows of GRB 050509B (Gehrels et al. 2005), GRB 050709 (Villasenor et al. 2005), and GRB 050724 (Barthelmy et al. 2005b) demonstrate that sGRBs have a cosmological origin.

Although the study of sGRBs developed rapidly, the central engine of sGRBs is still under debate (Virgili et al. 2011). The most popular model is the merger of the compact object binary (Eichler et al. 1989; Narayan et al. 1992), such as binary neutron stars (NSs) or black hole (BH)-neutron star binaries. The location of sGRBs (Fong & Berger 2013) and the presence of kilonova emission (Berger et al. 2013; Tanvir et al. 2013) provide evidence for this model. One important prediction of this model is that sGRBs should be accompanied with gravitational wave radiation (Abramovici et al. 1992; Narayan et al. 1992). Recently, advanced LIGO detected some gravitational wave events, GW 150914 (Abbott et al. 2016b), GW 151221 (Abbott et al. 2016a), GW 170104 (Abbott et al. 2017a), and GW 170814 (Abbott et al. 2017b). Notably, GW 170817, which is associated with GRB 170817A, is believed to originate from the merge of binary neutron stars, which provides strong evidence for this model (Abbott et al. 2017c).

The formation rate of long GRBs has been extensively explored (Kistler et al. 2008; Wang & Dai 2009; Wanderman & Piran 2010; Coward et al. 2013). Although the number of observed sGRBs is increasing, only a small fraction of sGRBs have redshift measurements. Therefore, it is very difficult to estimate the sGRB formation rate. The local formation rate, estimated by previous works, ranges from 0.1 events Gpc$^{-3}$ yr$^{-1}$ to 400 events Gpc$^{-3}$ yr$^{-1}$ (Guetta & Piran 2005, 2006; Nakar et al. 2006; Guetta & Stella 2009; Siellez et al. 2014; Sun et al. 2015; Paul 2017). These results are mainly determined by fitting the peak flux distribution with a given function form. So the derived formation rate of sGRBs is model dependent. Another challenge to estimate the formation rate is the selection effects for sGRBs. The most important selection effect is the flux limit of satellites; thus, the observed data may ignore some dim sGRBs. The Lynden-Bell $c^-$ method can deal with a flux-limit sample, which is proposed by Lynden-Bell (1971). This method has been used in long GRBs (Lloyd-Ronning et al. 2002; Yonetoku et al. 2004; Kocevski & Liang 2006; Wu et al. 2012; Petrosian et al. 2015; Yu et al. 2015). Using the $E_p$–$L_p$ correlation and the Lynden-Bell $c^{-}$ method, Yonetoku et al. (2014) found that the formation rate of sGRBs follows SFRs at $z < 4.0$ with local rate $0.63^{+0.31}_{-0.30}$ events Gpc$^{-3}$ yr$^{-1}$. Besides, Abbott et al. (2017c) obtained the local formation rate of binary neutron stars, which is $1540^{+3200}_{-1300}$ Gpc$^{-3}$ yr$^{-1}$ based on the detection of GW 170817 at about 40 Mpc. Several selection effects, such as Malmquist bias, redshift desert, and the fraction of afterglows missing because of host galaxy dust extinction, are considered for Swift long GRBs (Coward et al. 2013).

In this paper, the $E_p$–$L_p$ correlation is obtained with 16 sGRBs. Using this correlation, we get the pseudo redshifts of 284 Fermi sGRBs. Then we derive the luminosity function and formation rate of sGRBs using the Lynden-Bell $c^-$ method. Last, we estimate the number of gravitational wave events associated with sGRBs. This paper is organized as follows. In the next section, we derive the $E_p$–$L_p$ correlation and the pseudo redshifts of Fermi/GBM sGRBs. In Section 3, the luminosity function and formation rate of sGRBs are determined using Lynden-Bell $c^-$ method. In Section 4, we test our results with Monte Carlo simulations. Finally, we give conclusions and discussion in Section 5. Throughout this paper, we adopt the flat ΛCDM model with $\Omega_m = 0.27$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.


2. sGRB Sample

The number of sGRBs with measured redshifts is very small. In order to constrain the luminosity function and formation rate, we derive the pseudo redshifts of sGRBs using the correlation between the peak energy $E_p$ and the peak luminosity $L_p$ (Tsutsui et al. 2013). In this section, we fit the $E_p$-$L_p$ correlation with more sGRBs.

We collect 16 sGRBs with measured redshifts. In Table 1, we list the properties of these 16 sGRBs, including name, duration in the rest-frame $t_{90}^{\text{rest}} = T_{90}/(1+z)$, measured redshift, spectral peak energy $E_p$, and peak luminosity $L_p$ in 64 ms of the observer-frame time bin. It should be noted that the first eight sGRBs are consistent with those of Tsutsui et al. (2013).

The Band function (Band et al. 1993)

\[
f(E) = \begin{cases} 
A \left( \frac{E}{100 \text{ keV}} \right)^{\alpha} \exp \left( \frac{-(2+\alpha)E}{E_p} \right) E < \frac{(\alpha-\beta)E_p}{2+\alpha}, \\
A \left( \frac{E}{100 \text{ keV}} \right)^{\beta} \exp^{-\alpha} \left( \frac{(\alpha-\beta)E_p}{2+\alpha} \right) \left( \frac{(\alpha-\beta)E_p}{2+\alpha} \right)^{\alpha-\beta} E \geq \frac{(\alpha-\beta)E_p}{2+\alpha},
\end{cases}
\]

is used to fit the spectra of sGRBs. The peak luminosity is calculated in the $1-10^{5}$ keV energy range. The photon indices are set as $\alpha = -1$ and $\beta = -2.25$ for those that lack observational constraints (Schaefer 2007; Wang et al. 2011).

For sGRBs observed by Swift, the 64 ms peak flux is estimated by correcting the 1 s peak flux with the ratio of the 64 ms and 1024 ms peak counts in the 64 ms binned light curve provided by Swift (Wanderman & Piran 2015).

We fit the $E_p$-$L_p$ correlation with the linear form

\[
L_p = a \left( \frac{E_p}{100 \text{ keV}} \right)^{b}.
\]
Zou et al. 2017]. If Lorentz factor $\Gamma = 50$ and $\zeta - \theta_{j} = 11^{\circ}$ are assumed, GRB 170817A follows the $E_p-L_p$ correlation.

We select 284 sGRBs observed by Fermi/GBM (Gruber et al. 2014; von Kienlin et al. 2014; Narayana Bhat et al. 2016). The pseudo redshifts of these sGRBs are obtained through Equation (4). In Table 2, we list the name of sGRB, the rest-frame duration $T_{90}$, the pseudo redshift $z$, the peak flux $F_p$ at 64 ms time intervals, the peak energy $E_p$, the photon indices $\alpha$, $\beta$, and the peak luminosity $L_p$ within energy range $1-10^5$ keV. The photon indices are set as $\alpha = -1$, $\beta = -2.25$ for sGRBs without observational constraints.

In order to study the luminosity function, we introduce the flux limit of the Fermi/GBM. According to Band (2003), the GBM flux limit is weakly dependent on peak energy $E_p$. Therefore, we set the flux limit as a constant, which has been widely used in the literature. Band (2003) calculated the flux limit for accumulation time $\Delta t = 1$ s. After converting it to $\Delta t = 64$ ms, we find that the flux limit is about 2.3 photons cm$^{-2}$ s$^{-1}$. Besides, the flux distribution of sGRBs, which were observed by Fermi/GBM, indicated that the flux limit on a 64 ms timescale is 2.3 photons cm$^{-2}$ s$^{-1}$ (Narayana Bhat et al. 2016). This value is also used in Clark et al. (2015). Therefore, we set the photon flux limit as 2.3 photons cm$^{-2}$ s$^{-1}$. The distribution of the pseudo redshifts and 64 ms luminosity is shown in Figure 2. The blue line is the flux limit $F_{\text{limit}} = 2.3$ photons cm$^{-2}$ s$^{-1}$. We remove the sGRBs with $z > 3$, because the maximum redshift observed for sGRBs is 2.609. Hereafter, we use 239 sGRBs that are brighter than the flux limit for further analysis.

3. Luminosity Function and Formation Rate

3.1. Lynden-Bell $c^{-}$ Method

Many previous works fitted the luminosity function with a given function form. These results have a strong dependence on the function form. In this paper, we use the Lynden-Bell $c^{-}$ method to derive the luminosity function and the formation rate of sGRBs. The Lynden-Bell $c^{-}$ method is an efficient method to determine the distribution of the redshift and the luminosity function of astronomical objects with a truncated sample. Lynden-Bell (1971) developed this method and derived the luminosity function and density evolution for quasars. This method has been used to study pulsars (Desai 2016), long GRBs (Lloyd-Ronning et al. 2002; Yonetoku et al. 2004; Petrov Yonetoku et al. 2014; Yu et al. 2015; Tsvetkova et al. 2017) and sGRBs (Yonetoku et al. 2014). If the luminosities and redshifts of sGRBs are independent, the distribution of luminosity and redshift should be $\Psi(L, z) = \psi(L) \rho(z)$, where $\psi(L)$ is the luminosity function and $\rho(z)$ represents the formation rate of sGRBs. However, there exists a significant degeneracy between luminosity and redshift (Lloyd-Ronning et al. 2002). Therefore, $\Psi(L, z)$ should be written as $\Psi(L, z) = \rho(z) \psi(L/g(z))/g(z)$, where $g(z)$ is the correlation between the luminosity and redshift. The luminosity at redshift $z = 0$ is $L_0 = L/g(z)$. The goal of our analysis is to obtain the formation rate $\rho(z)$ and the local luminosity function $\psi(L/g(z))$.

The first step is to remove the effect of luminosity evolution. We take the evolution function form as $g(z) = (1 + z)^k$, which has been used in previous works (Lloyd-Ronning et al. 2002; Yonetoku et al. 2014; Yu et al. 2015). In order to determine the value of $k$, we use the $\tau$ statistical method (Efron & Petrov Yonetoku 1992). For each point $(L_i, z_i)$, we can define the associated set $J_i$ as

$$J_i = \{ | z_j \geq L_i, z_j \leq z_i \}_{\max} \},$$

where $L_i$ is the luminosity of $i$th sGRB and $z_i$ is the maximum redshift at which the sGRBs with the luminosity $L_i$ can be detected by satellite. We plot this region as a green rectangle in Figure 2. We define the number of sGRBs in this region as $n_i$ and the number of sGRBs with redshifts less than or equal to $z_i$ as $R_i$. The expected mean and the variance of $R_i$ should be $E_i = n_i^{1/2}$ and $V_i = n_i^{1-1/2}$, respectively.

The statistic $\tau$ to test the dependence between luminosity and redshift is

$$\tau = \sum_i (R_i - E_i) \sqrt{\sum_i V_i}.$$  

If luminosity and redshift are independent, $R_i$ should be uniformly distributed between 1 and $n_i$. Therefore, $\tau$ should be zero. We change the value of $k$ until the test statistic $\tau$ is zero. Finally, we find that the best fitting is $k = 4.47^{+0.47}_{-0.29}$, which is similar to Paul (2017). He obtained $k = 4.269 \pm 0.134$ for Fermi sGRBs. We show the distribution of non-evolving luminosity and redshift in Figure 3.

3.2. Luminosity Function

After removing the effect of luminosity evolution through $L_0 = L/(1 + z)^k$, the cumulative luminosity function can be derived with a nonparametric method from the following equation (Lynden-Bell 1971; Efron & Petrov Yonetoku 1992)

$$\psi(L_0) = \prod_{j<i} \left(1 + \frac{1}{N_j} \right),$$

where $j < i$ means that the $j$th sGRB has a larger luminosity than $i$th sGRB. The cumulative luminosity function is shown in Figure 4. We use a broken power-law form to fit the luminosity function. The best fit is given by

$$\psi(L_0) \propto \begin{cases} L_0^{0.29 \pm 0.01} & L_0 < L_0^b \\ L_0^{-1.07 \pm 0.01} & L_0 > L_0^b \end{cases}$$
with the break luminosity \( L_b = 8.26 \times 10^{50} \text{ erg s}^{-1} \). Our result is marginally consistent with Yonetoku et al. (2014) for bright sGRBs. They get \( y \mu - 0.84 \) between the luminosity \( 10^{51} \) and \( 10^{53} \) erg s\(^{-1}\). It should be noted that this is the luminosity function at \( z = 0 \). The luminosity function at redshift \( z \) is \( \psi(L_0)(1 + z)^{4.47} \).

### 3.3. sGRB Formation Rate

To obtain the formation rate of sGRBs, we define \( J' \) as

\[
J'_i = \{ j | L_j > L_j^{\text{lim}}, z_j < z_i \},
\]

where \( z_i \) is the redshift of \( i \)th sGRB, and \( L_j^{\text{lim}} \) is the minimum luminosity, which can be observed at redshift \( z_i \). The number of sGRBs in this region is \( M_i \). Similar to deriving the luminosity function, we can obtain the cumulative redshift distribution as

\[
\phi(z_i) = \prod_{j < i} \left( 1 + \frac{1}{M_j} \right)
\]

The formation rate of sGRBs can be derived from

\[
\rho(z) = \frac{d\phi(z)}{dz} (1 + z) \left( \frac{dV(z)}{dz} \right)^{-1},
\]

where the factor \((1 + z)\) is due to the cosmological time dilation. The differential comoving volume \( dV(z)/dz \) is

\[
\frac{dV(z)}{dz} = 4\pi c H_0 \left( \frac{1}{H_0} \right)^3 \left( \int_0^z \frac{dz}{\sqrt{1 - \Omega_m - \Omega_m (1+z)^3}} \right)^2 \times \frac{1}{\sqrt{1 - \Omega_m - \Omega_m (1+z)^3}}.
\]
The cumulative redshift distribution is plotted in Figure 5. We also show $(1 + z)\frac{d\Phi(z)}{dz}$ in Figure 6. From this figure, it is obvious that $(1 + z)\frac{d\Phi(z)}{dz}$ increases quickly at $z < 0.8$, remains constant at $0.8 < z < 1.5$, and then decrease quickly at $z > 1.5$. This profile is similar as the formation rate derived by Yonetoku et al. (2014). Figure 7 gives the formation rate of sGRBs. The best fitting of $\rho(z)$ is

$$
\rho(z) \propto \begin{cases} 
(1 + z)^{-3.08 \pm 0.06} & z < 1.60 \\
(1 + z)^{-4.98 \pm 0.03} & z \geq 1.60
\end{cases}
$$

(13)

The formation rate $\rho(z)$ decreases at all redshift ranges, which is dramatically different from Yonetoku et al. (2014). Because the result of Yonetoku et al. (2014) is similar to Figure 6, they may omit the differential comoving volume $dV(z)/dz$ term in their calculation, which has been discussed in Yu et al. (2015). The local event rate is $7.53 \text{ Gpc}^{-3} \text{ yr}^{-1}$. Fong et al. (2015) also found that the local formation rate is $10 \text{ Gpc}^{-3} \text{ yr}^{-1}$, which is consistent with our results.

4. Testing with the Monte Carlo Simulation

In this section, we use Monte Carlo simulations to test our results. We simulate a set of points $(L_{0}, z)$, which satisfies Equations (8) and (13). The luminosity function of Equation (8) is at redshift $z = 0$. So we transform the luminosity $L_{0}$ to $L = L_{0}(1 + z)^{a}$. Then we obtain a set of points $(L, z)$, which is similar to observed data. We simulate 200,000 points and divide them into 200 groups. In each group, 200 points are selected as pseudo data points. We perform the same analysis as above to obtain the luminosity function and formation rate of sGRBs.

Our results are shown in Figure 8. In panel (a), the luminosity–redshift distribution is shown. We select one sGRB from each group and get 200 pseudo sGRBs to compare with the observed data. The blue points and red points represent the simulated data and observed data, respectively. The solid line is the flux limit $2.3 \text{ photons cm}^{-2} \text{ s}^{-1}$. It is obvious that the simulated data and the observed data have a similar distribution. In panels (b), (c), and (d), the blue lines are the cumulative luminosity function, cumulative redshift distribution, and log $N$–log $S$ distribution derived from the simulated data. The red lines and yellow lines are observed data and the mean of the simulated data, respectively. We perform the Kolmogorov–Smirnov test between observed data and the mean distribution of simulated data. The $p$ value for panels (b), (c), and (d) are 0.29, 0.99, and 0.94, respectively. Meanwhile, the distributions of the observed data lie in the region of the simulated data. Therefore, the cumulative luminosity function and formation rate are reliable.

5. Conclusions and Discussion

In this paper, we first use 16 sGRBs with measured redshifts to fit the $E_{p}–L_{p}$ correlation. Using this correlation, we obtain the pseudo redshifts of 284 sGRBs observed by Fermi/GBM, which are listed in Table 2. Then, the Lynden-Bell $c^{-}$ method is used to study the luminosity function and the formation rate of sGRBs. The effect of luminosity evolution is removed by $L_{0} = L/(1 + z)^{k}$, where $k = 4.47_{-0.29}^{+0.47}$. After removing the effect of luminosity evolution, we derive the cumulative luminosity function. The result is shown in Figure 4, which can be fitted with a broken power law as $\psi(L_{0}) \propto L_{0}^{-0.29 \pm 0.01}$ for $L_{0} < L_{0}^{b}$ and $\psi(L_{0}) \propto L_{0}^{-1.07 \pm 0.01}$ for $L_{0} > L_{0}^{b}$, with $L_{0}^{b} = 8.26 \times 10^{50} \text{ erg s}^{-1}$. Wanderman & Piran (2015) found
The luminosity function with power-law indices $-0.94$ for dim bursts and $-2.0$ for luminous bursts. The break luminosity is $2 \times 10^{52}$ erg s$^{-1}$. These indices and the break point are much larger than our results. The reason is that they do not consider the effect of luminosity evolution. Considering the luminosity evolution, Yonetoku et al. (2014) determined the index $-0.84_{-0.07}^{+0.07}$ for bright sGRBs, which is consistent with our result.

In Figure 6, we show the evolution of $(1 + z)^\frac{\text{d}L(z)}{\text{d}z}$, which increases quickly at $z < 0.8$, remains approximately constant at $0.8 < z < 1.5$, and decreases rapidly at $z > 1.5$. Figure 7 shows the formation rate of sGRBs. We find that the formation rate is decreasing quickly. The best fit is $\rho(z) \propto (1 + z)^{-1.08}$ for $z < 1.60$ and $\rho(z) \propto (1 + z)^{-4.98}$ for $z \geq 1.60$. Obviously, the formation rate is in contrast to previous estimations by Wanderman & Piran (2015), Ghirlanda et al. (2016), and Yonetoku et al. (2014). By assuming the formation rate of sGRBs has a time delay to the star formation rate, Wanderman & Piran (2015) and Ghirlanda et al. (2016) found that the formation rate is increasing at $z < 1.5$ and decreasing at $z > 1.5$. The Lynden-Bell $c$ method is also used by Yonetoku et al. (2014) to study the formation rate of sGRBs. They found the formation rate increases at $z < 0.6$ and remains constant at $0.6 < z < 2$, which is similar to the evolution of $(1 + z)^\frac{\text{d}L(z)}{\text{d}z}$ shown in Figure 6. Therefore, they may omit the differential comoving volume term.

The local formation rate of sGRBs is $7.53 \text{ Gpc}^{-3} \text{ yr}^{-1}$, which is consistent with that of Fong et al. (2015). If only the GRB 170817A that occurred at about 40 Mpc is considered, the local rate of sGRBs is $\sim 463 \text{ Gpc}^{-3} \text{ yr}^{-1}$. Zhang et al. (2017) obtained that the event rate is $190_{-160}^{+440} \text{ Gpc}^{-3} \text{ yr}^{-1}$, which is similar to our result. Some estimations are lower than our result, for example, $0.51_{-0.31}^{+0.36} \text{ Gpc}^{-3} \text{ yr}^{-1}$ (Ando 2004) and $0.63_{-0.31}^{+0.36} \text{ Gpc}^{-3} \text{ yr}^{-1}$ (Yonetoku et al. 2014). Besides, Nakar et al. (2006) and Guetta & Piran (2006) obtained the formation rate as $40 \pm 12 \text{ Gpc}^{-3} \text{ yr}^{-1}$ and $30_{-50}^{+50} \text{ Gpc}^{-3} \text{ yr}^{-1}$, respectively, which are larger than our result.

If we set the beaming factor as $I_b = 27_{-18}^{+158}$ (Fong et al. 2015), the local event rate of sGRBs including the off-axis ones is $\rho_{0,\text{all}} = 203.31_{-135.34}^{+152.09} \text{ Gpc}^{-3} \text{ yr}^{-1}$. At present, the horizon of aLIGO and Virgo for the merger of NS–NS is 80–120 Mpc (Abbott et al. 2016c). If we suppose that the sGRBs arise from the mergers of NS–NS binaries, the event rate of the gravitational wave is $0.85_{-0.3}^{+1.55} \text{ events yr}^{-1}$. The horizon for NS–NS will increase to 200 Mpc in 2019 (Abbott et al. 2016c). Then aLIGO will detect $6.8_{-1.8}^{+5.3}$ events per year. If we assume that the mass of a black hole is 5 $M_{\odot}$, the range of BH–NS is approximately a factor of 1.6 larger than the NS–NS range. Thus it is expected to detect $3.48_{-1.48}^{+19.75}$ events every year for now and $27.89_{-18.59}^{+158.05} \text{ events every year in 2022}$.

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