IL NUOVO CIMENTO Vol. 28 C, N. 4-5 Luglio-Ottobre 2005
DOI 10.1393/ncc/i2005-10133-2

GRB formation rate derived by the E_p-luminosity relation(*)

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(ricevuto il 23 Maggio 2005; pubblicato online il 12 Ottobre 2005)

Summary. — We estimate a GRB formation rate based on the new relation between the spectral peak energy (E_p) and the peak luminosity. This relation is derived combining the data of E_p and the peak luminosities by BeppoSAX and BATSE, and it looks considerably tighter and more reliable than the relations suggested by the previous works. Using the new E_p-luminosity relation, we estimate redshifts of the 689 GRBs without known distances in the BATSE catalog and derive a GRB formation rate as a function of the redshift. For the redshift range of $0 \le z \le 2$, the GRB formation rate increases and is well correlated with the star formation rate while it keeps constant toward $z \sim 12$.

PACS `98.80.Es` – Observational cosmology.
PACS `01.30.Cc` – Conference proceedings.

1. – Introduction

Many ground-based telescopes observed optical afterglows of GRBs and measured their redshifts by detecting the absorption and/or emission lines of the interstellar matter in the host galaxy. However, the number of GRBs with measured redshift is only a fraction of all GRBs detected with the BATSE, BeppoSAX, HETE-II and INTEGRAL satellites. We have still only about 40 GRBs with the known redshifts. The most of them occur at the cosmological distance, and the current record holder is GRB 000131 at $z = 4.5$ [2]. According to the brightness distribution of the GRBs with the known redshifts, much more distant GRBs such as at $z \sim 20$ are potentially detectable [4]. If we can establish a method for estimating the intrinsic brightness in the characteristics of the prompt gamma-ray emission, we can use the GRB brightness as a standard candle to determine the redshifts of majority of GRBs, which enables us to explore the early universe out to $z \sim 20$.

In this paper, we use a new and much tighter relation to estimate the redshifts based on the E_p-luminosity relation of the prompt gamma-ray emission, combining not only the BeppoSAX data but also the 11 BATSE GRBs with the known redshifts. Importantly, the correlation is high and the uncertainty of our relation is much less than those of the

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(*) Paper presented at the "4th Workshop on Gamma-Ray Burst in the Afterglow Era", Rome, October 18-22, 2004.

previous works using the lags and variability [7, 10, 11]. Applying the new relation, we estimate the redshifts of 689 GRBs and then demonstrate the GRB formation rate out to $z \sim 12$. Throughout the paper, we assume the flat-isotropic universe with $\Omega_m = 0.32$, $\Omega_\Lambda = 0.68$ and $H_0 = 72$ km s^{-1}Mpc^{-1}.

2. – Data analysis

First, we analyzed the 11 GRBs in the BATSE archive with the known redshifts. Following the previous work by [1], we calculate E_p of the burst average spectra and also the peak luminosity integrating between 1 s at the peak, because it is the better distance indicator than the burst average luminosity.

We used the spectral data detected by the BATSE LAD detectors, and performed the spectral analysis with the standard data reduction for each GRB. We extracted the burst data in the $\sim T_{90}$ interval for each burst, and subtracted the background spectrum derived from the average spectrum before and after the GRB in the same data set. We adopted the spectral model of smoothly broken power law [3]. The model function is described below.

$$N(E) = \begin{cases} A\left(\frac{E}{100\ \mathrm{keV}}\right)^{\alpha} \exp\left[-\frac{E}{E_0}\right], \\ A\left(\frac{E}{100\ \mathrm{keV}}\right)^{\beta} \left(\frac{(\alpha-\beta)E_0}{100\ \mathrm{keV}}\right)^{\alpha-\beta} \exp\left[\beta-\alpha\right], \end{cases} \tag{1}$$

for $E \leq (\alpha-\beta)E_0$ and $E \geq (\alpha-\beta)E_0$, respectively. Here, $N(E)$ is in units of photons cm^{-2} s^{-1} keV^{-1}, and E_0 is the energy at the spectral break. α and β is the low- and high-energy power law index, respectively. For the case of $\beta < -2$ and $\alpha > -2$, the peak energy can be derived as $E_p = (2+\alpha)E_0$, which corresponds to the energy at the maximum flux in νF_ν spectra. The peak luminosity with the proper k-correction can be calculated as $L = 4\pi d_{\mathrm{L}}^2 F_\gamma k_c$, where d_{L} and F_γ is the luminosity distance and the observed peak flux integrated between 30–10000 keV, respectively. The k-correction factors (k_c) are estimated by the same method of [1], and consistent with ones of [6] and do not exceed 2.

3. – E_p-luminosity relation and redshift estimation

In fig. 1 (left), we show the peak luminosities in units of 10^{52} ergs s^{-1} as a function of the peak energy, $E_p(1+z)$, in the rest frame of each GRB. For GRB 980703, only a lower limit of $E_p(1+z)$ is set because of the spectral index $\beta > -2$. The BeppoSAX results reported in previous work [1] are also included in the same figure after correcting the energy range. Here, we converted the peak fluxes of [1] (see table 1 of their paper) into the peak luminosity of our energy range of 30–10000 keV using their spectral parameters. Therefore, we can combine our 11 BATSE results with BeppoSAX results in the same plane. This is the key of the present work.

There is a high and tighter positive correlation between the $E_p(1+z)$ and the L than the previous works. The linear correlation coefficient including the weighting factors is 0.958 for 14 degree of freedom (16 samples with firm redshifts; open and filled squares in fig. 1) for the $\log[E_p(1+z)]$ and the $\log[L]$. The chance probability shows extremely low value of 5.31×10^{-9}. When we adopt the power-law model to the E_p-luminosity relation, the best-fit function is

$$\frac{L}{10^{52}\ \mathrm{ergs/s}} = (2.34^{+2.29}_{-1.76}) \times 10^{-5} \left[\frac{E_p(1+z)}{1\ \mathrm{keV}}\right]^{2.0\mp0.2}, \tag{2}$$

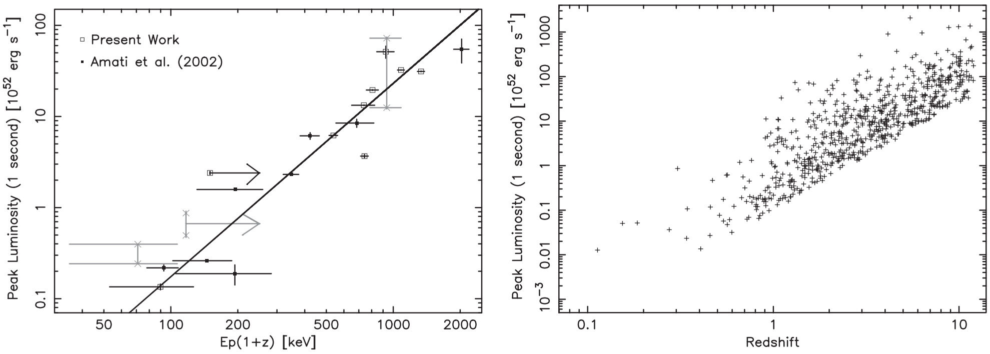

Fig. 1. – The left panel is the E_p-luminosity relation. The open squares are our present results with BATSE. The results of BeppoSAX [1] are also shown as the filled squares. The right panel is the distribution of the peak luminosity *vs.* redshift derived from the E_p-luminosity relation. The truncation of the lower end of the-luminosity is caused by the flux limit of $F_{\mathrm{limit}} = 2 \times 10^{-7}\,\mathrm{ergs\,cm^{-2}\,s^{-1}}$.

where the uncertainties are 1 σ error.

Using this E_p-luminosity relation, we can estimate the redshift from E_p and the 1 s peak flux. In other words, the E_p-luminosity relation becomes a possible redshift indicator which seems to be much better than the spectral time-lag and/or the variability of GRBs. We performed spectral analyses for 689 GRBs without known distance, and obtained the spectral parameters as well as the flux information. In fig. 1 (right), we show the distribution in (z, L) plane truncated by the flux limit.

4. – GRB formation rate

Based on the redshift distribution in the previous section, We can derive the GRB formation rate in differential form. In fig. 2, we show the relative GRB formation rate $\rho(z)$ in unit proper volume. The best result is described by

$$\rho(z) \propto \begin{cases} z^{6.0\pm1.4} & , \text{ for } z < 2, \\ z^{0.4\pm0.2} & , \text{ for } z > 2. \end{cases} \tag{3}$$

The upper and the lower bound caused by the uncertainty of the E_p-luminosity relation is shown by the dotted lines. The result indicates that the GRB formation rate does not decrease toward $z \sim 12$. This tendency is consistent with the previous works using the GRB variability [7, 8] and the spectral time-lag [10, 11, 9]. On the other hand, the star formation rates (SFRs) measured in UV, optical, and infrared tend to decrease (or keep constant) at the higher redshift of $z \geq 2$. Recently, it is widely believed that the origin of the long duration GRBs is the collapse of a massive star. Hence our result may imply that either the formation rate of the massive star or the fraction of GRB progenitor in massive stars at the high redshift should be significantly larger than the present value.

Band *et al.* [5] claim that 88% of the BATSE bursts are inconsistent with the E_p-E_{iso} relation because the redshifts to satisfy the relation cannot be found in the redshift range of $0 \leq z \leq 20$. They concluded that the E_p-E_{iso} relation is caused by the selection effect. In this paper, we found physically reasonable redshift ($0 \leq z \leq 12$) based on both the E_p-luminosity relations. This result corresponds to the fact that the

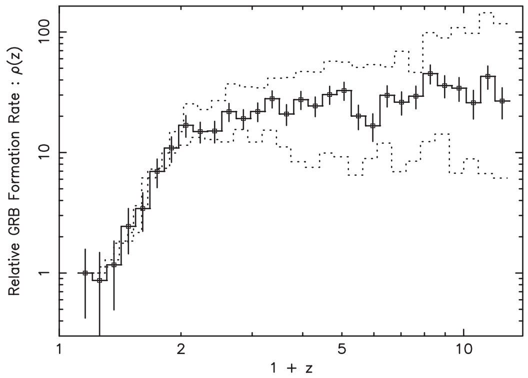

Fig. 2. – The relative GRB formation rate normalized at the first point. The solid line is the result based on the best fit of E_p-luminosity relation. Two dotted lines indicate the upper and lower bounds caused by the uncertainty of E_p-luminosity relation, and they are also normalized at the first point. The error bars accompanying open squares represent the 1 σ statistical uncertainty of each point.

E_p-luminosity relation can pass the test questioned by [5]. Therefore we conclude that this relation can be indeed the real relation not the selection effects.

Finally, several authors suggested the existence of the luminosity evolution which is the redshift dependence of the intrinsic luminosity. One of the possible interpretation about the luminosity evolution is the evolution of GRB progenitor itself (*e.g.,* mass; gravitational energy release) and/or the jet opening angle evolution. In the case of the jet evolution, the GRB formation rate shown in fig. 2 may be an underestimate since the chance probability to observe the high-z GRB will decrease. If so, the GRB formation rate may increase more rapidly toward the higher redshift. On the another hand, in the progenitor evolution, the functional form of the GRB formation rate in fig. 2 is a reasonable estimate. More detail informations and results are published in Yonetoku *et al.* [12].

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