Are long gamma-ray bursts standard candles?

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ABSTRACT

Gamma-ray bursts (GRBs) are widely proposed as an effective probe to trace the Hubble diagram of the Universe in high redshift range. However, the calibration of GRBs is not as easy as that of type-Ia supernovae (SNe Ia). Most calibrating methods at present take use one or some of the empirical luminosity corrections, e.g., Amati relation. One of the underlying assumptions of these calibrating methods is that the empirical correlation is universal over all redshifts. In this paper, we check to what extent this assumption holds. Assuming that SNe Ia exactly trace the Hubble diagram of the Universe, we re-investigate the Amati relation for low redshift ($z < 1.4$) and high redshift ($z > 1.4$) GRBs, respectively. It is found that the Amati relation of low-$z$ GRBs differs from that of high-$z$ GRBs at more than 3$\sigma$ confidence level. This result is insensitive to cosmological models.

Key words: cosmological parameters – gamma-ray burst: general – supernovae: general

1 INTRODUCTION

Gamma-ray bursts (GRBs) are the most luminous explosions in the Universe since the big bang. The isotropic equivalent energy they released in a few seconds can be as large as $10^{48} \sim 10^{55}$ ergs. For recent reviews, see, e.g., Piran (1999); Meszéros (2002, 2006); Kumar & Zhang (2013). Thanks to their extremely brightness, GRBs are detectable up to redshift $z \gtrsim 9$ (Salvaterra 2015). For example, the most distant GRB known toaday is GRB 090429B, whose redshift is as high as $z \approx 9.4$ (Cucchiara et al. 2011). Due to their high redshift properties, GRBs are often proposed as potential candles to trace the Hubble diagram of the Universe in the high redshift range. In fact, GRBs have already been widely used, together with other candles, such as type-Ia supernovae (SNe Ia), to constrain the cosmological parameters (Schaefer 2003; Bloom, Frail & Kulkarni 2003; Xu, Dai & Liang 2005; Firmani et al. 2005; Liang & Zhang 2005; Firmani et al. 2006; Schaefer 2007; Liang et al. 2008; Liang & Zhang 2008; Wei & Zhang 2009; Wei 2010; Wang, Qi & Dai 2011; Capozziello et al. 2012; Wei, Wu & Melia 2013; Velten, Montiel & Carneiro 2013; Cai et al. 2013; Breton & Montiel 2013; Chang et al. 2014; Capo & Jakobsson 2014; Cuzzatto, Medeiros & de Moraes 2014; Wang & Wang 2014; Wang, Dai & Liang 2015; Li, Ding & Zhu 2015). The consistent luminosity of SNe Ia makes them to be the ideal distance indicators in tracing the Hubble diagram of the local (low-redshift) universe. However, since we have little knowledge about the explosion mechanism of GRBs, the GRB candle is much less standard than the SN Ia candle.

Nevertheless, one can still calibrate GRBs using the empirical luminosity correlations found in long GRBs. These correlations includes Amati relation ($E_{\text{peak}} - E_{\text{iso}}$) (Amati et al. 2002; Amati 2003, 2006), Ghirlanda relation ($E_{\text{peak}} - E_{\gamma}$) (Ghirlanda, Ghisellini & Lazzati 2004), Yonetoku relation ($E_{\text{peak}} - L_{\text{iso}}$) (Yonetoku et al. 2004), Liang-Zhang relation ($t_{b} - E_{\text{peak}} - E_{\text{iso}}$) (Liang & Zhang 2003), Firmani relation ($T_{0.45} - E_{\text{peak}} - L_{\text{iso}}$) (Firmani et al. 2006b), lag-luminosity relation ($\tau_{\text{lag}} - L_{\text{iso}}$) (Norris, Marani & Bonnell 2004), variability-luminosity relation ($V - L_{\text{iso}}$) (Fenimore & Ramirez-Ruiz 2000).

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Among these luminosity correlations, the Amati relation is most widely used. This is partly because that the spectrum properties such as the peak energy $E_{\text{peak}}$, the spectrum indices $\alpha$ and $\beta$, and the photon fluence $S$ are necessary to analyze the Amati relation can be easily observed with enough precision, so that the number of available GRBs is large. Unfortunately, all of these correlations depend on a specific cosmological model. Therefore, circularity problem occurs when using GRBs to constrain the cosmological parameters. Recently, some model-independent methods were proposed to calibrate GRBs, such as the Bayesian method (Firmani et al. 2003), the luminosity distance method (Ghirlanda et al. 2004; Liang & Zhang 2005), and the scatter method (Ghirlanda et al. 2004), etc.. Actually, these methods still can’t completely solve the circularity problem.

A completely model-independent method free of circularity problem is using distance ladder to calibrate GRBs (Liang et al. 2008, Liang & Zhang 2008, Wei & Zhang 2009, Wei 2010). The main procedures are as follows: Firstly, calculate the distance moduli for the low-redshift (e.g., $z < 1.4$) GRBs by using cubic interpolation from SNe Ia (e.g., Union2). Thus, the distance as well as the isotropic equivalent energy of low-$z$ GRBs can be derived. Then we can obtain the empirical luminosity correlations (such as Amati relation) from the low-$z$ GRBs. By directly extrapolating the empirical luminosity correlations to high-$z$ (e.g., $z > 1.4$) GRBs, we can inversely obtain the distance moduli for high-$z$ GRBs. Since the distance moduli of SNe Ia are directly extracted from their light curves without involving any cosmological model, this calibrating method is of course completely model-independent. Recently, a similar method was proposed by Liu & Wei (2014). The only difference is that they used the Padé approximation (Pade 1892) instead of the cubic interpolation to derive the distance moduli of low-$z$ GRBs. An underlying, but not being proven assumption of these methods is that the empirical luminosity correlations are universal over all redshifts. If the empirical luminosity correlations evolve with redshift, these calibrating methods might be invalid. In fact, Wang, Qi & Dai (2011) have already investigated six empirical luminosity correlations in different redshift ranges. They found that the slope of Amati relation of high-$z$ GRBs is smaller than that of low-$z$ GRBs, although the intercept does not vary significantly with redshift. Similar features were found in the rest five luminosity correlations. Due to the large uncertainties, they concluded that no significant evidence for the redshift evolution of the luminosity correlations was found. However, in another paper (Li 2007), the author has showed that the Amati relation varies with redshifts systematically and significantly.

In this paper, we focus on checking the redshift dependence of Amati relation. Firstly, we use the Union2.1 dataset (Suzuki et al. 2012) to constrain the Hubble diagram of the Universe in the redshift range of $z < 1.4$. Then we directly extrapolate the Hubble diagram to high redshift range. By assuming that GRBs follow the same Hubble diagram, we can calculate their luminosity distance and isotropic equivalent energy. Finally, we study the Amati relation for the low-$z$ ($z < 1.4$) and high-$z$ ($z > 1.4$) GRBs, respectively. The GRB sample is taken from Liu & Wei (2014). This sample consists of 59 low-$z$ GRBs and 79 high-$z$ GRBs. The rest of the paper is arranged as follows: In section 2 we introduce the data and methodology that are necessary to our studies. We present our results in section 3. Finally, discussions and conclusions are given in section 4.

## 2 DATA AND METHODOLOGY

### 2.1 Union2.1 and Hubble diagram

SNe Ia are usually regarded as ideal distance indicators to trace the Hubble diagram of the Universe due to their consistent luminosity. The GRB candle, however, is much less standard than the SN Ia candle, since the explosion mechanism of GRBs is still not clearly known. Therefore, SNe Ia are often used to calibrate the distance moduli of GRBs. In this paper, we first use the recently published Union2.1 dataset (Suzuki et al. 2012) to constrain the cosmological parameters. The Union 2.1 dataset is a compilation of 580 well-observed SNe Ia in the redshift range $z \in [0.015, 1.415]$. All the SNe Ia have high-quality light curves, so their distance moduli can be extracted with high precision. The Hubble diagram can be tightly constrained by the Union2.1 dataset.

In the spatially-flat isotropic spacetime, the luminosity distance can be expressed as a function of redshift as

\[
d_L(z) = (1+z) \frac{c}{H_0} \int_0^z \frac{dz}{E(z)}
\]

where $c = 3 \times 10^8$ m s$^{-1}$ is the speed of light, $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ is the Hubble constant at present time, and $E(z) \equiv H(z)/H_0$ is the normalized Hubble parameter. In the $\Lambda$CDM model, we have

\[
E^2(z) = \Omega_M(1+z)^3 + (1-\Omega_M),
\]

where $\Omega_M$ is matter density today. In the $w$CDM model, we have

\[
E^2(z) = \Omega_M(1+z)^3 + (1-\Omega_M)(1+z)^{3(1+w)},
\]

where $w = p/\rho$ denotes the equation of state of dark energy. In the Chevallier-Polarski-Linder (CPL) parametrization (Chevallier & Polarski 2001; Linder 2003), the equation of state of dark energy is given as $w_{\text{CPL}} = w_0 + w_1 z/(1+z)$, and

\[
\Omega_M(1+z)^3 + (1-\Omega_M)(1+z)^{3(1+w)}.
\]
in this case, \( E(z) \) can be expressed as \( 3 \log d_L(z) \) + 25, where “log” is the logarithm of base 10. The best-fit cosmological parameters can be derived by minimizing Eq. (11). The uncertainty from \( d_L \) is absorbed into the intrinsic scatter \( \sigma_E \). We can rewrite Eq. (11) as

\[
y = a + bx,
\]

where “ln” represents the natural logarithm. The slope and intercept of Amati relation, i.e., \( b \) and \( a \) in Eq. (11), can be obtained by directly fitting Eq. (11) to the observed GRB data. However, the plot of the Amati relation in the \((x, y)\) plane shows significant error bars in both the horizontal and vertical axes. Besides, the intrinsic scatter dominates over the measurement errors. Therefore, the ordinary least-\( \chi^2 \) method does not work. We may get different best-fit parameters depending on whether we minimize the sum of squared residuals in the \( y \) axis or that in the \( x \) axis. To avoid such a problem, we use the fitting method presented in D’Agostini (2005). The joint likelihood function for the slope \( b \), intercept \( a \), and intrinsic scatter \( \sigma_E \) is given as

\[
\mathcal{L}(\sigma_E, a, b) \propto \prod_i \frac{1}{\sqrt{\sigma_E^2 + \sigma_y^2 + b^2 \sigma_z^2}} \times \exp \left[ -\frac{(y_i - a - bx_i)^2}{2(\sigma_E^2 + \sigma_y^2 + b^2 \sigma_z^2)} \right].
\]
Table 1. The best-fit cosmological parameters and their 1σ uncertainties from the Union2.1 dataset in three different cosmological models.

|         | $\Omega_M$       | $w$           | $w_0$         | $w_1$          |
|---------|------------------|---------------|---------------|----------------|
| $\Lambda$CDM | 0.2798 ± 0.0130 | -             | -             | -              |
| wCDM    | 0.2755 ± 0.0640  | -0.9903 ± 0.1431 | -             | -              |
| CPL     | 0.2962 ± 0.2224  | -             | -1.0090 ± 0.2249 | -0.2455 ± 2.9514 |

Table 2. The intrinsic scatters, intercepts and slopes of Amati relation for low-$z$ and high-$z$ GRBs in three different cosmological models.

|         | $\sigma_{\text{int}}$ | $a$           | $b$           |
|---------|------------------------|---------------|---------------|
| $\Lambda$CDM: low-$z$ | 0.3810 ± 0.0433 | 52.7326 ± 0.0568 | 1.6020 ± 0.1004 |
| high-$z$ | 0.3133 ± 0.0313 | 52.9459 ± 0.0476 | 1.3008 ± 0.1122 |
| wCDM: low-$z$ | 0.3810 ± 0.0433 | 52.7330 ± 0.0568 | 1.6023 ± 0.1004 |
| high-$z$ | 0.3132 ± 0.0313 | 52.9479 ± 0.0476 | 1.3010 ± 0.1121 |
| CPL: low-$z$  | 0.3810 ± 0.0433 | 52.7328 ± 0.0568 | 1.6020 ± 0.1004 |
| high-$z$ | 0.3135 ± 0.0313 | 52.9423 ± 0.0476 | 1.3005 ± 0.1122 |

3 RESULTS

To test the Amati relation, the Hubble diagram of the Universe should be known a priori. Thus, we first use the Union2.1 dataset to constrain the Hubble diagram of the Universe in low-redshift range ($z < 1.4$). The constraints on the parameters of three cosmological models are listed in Table 1. The quoted errors are of 1σ. In the fitting procedure, we fix the Hubble constant to be $H_0 = 70.0$ km s$^{-1}$ Mpc$^{-1}$. Note that the parameters of $\Lambda$CDM model and wCDM model can be tightly constrained. However, the constraint on the CPL model is rather loose, especially on the parameter $w_1$.

We directly extrapolate the Hubble diagram to the whole redshift range. Assuming that GRBs follow the same Hubble diagram, we can calculate the luminosity distance of GRBs from Eq. (1), as well as the isotropic equivalent energy from Eq. (8). We directly extrapolate the Hubble diagram to the whole redshift range. Assuming that GRBs follow the same Hubble diagram, we can calculate the luminosity distance of GRBs from Eq. (1), as well as the isotropic equivalent energy from Eq. (8). The Amati relation Eq. (11) is then used to fit the low-$z$ and high-$z$ GRBs, respectively. The best-fit parameters are listed in Table 2. The quoted errors are of 1σ. The $E_{\text{peak}} - E_{\text{iso}}$ correction is plotted in Figure 1 in logarithmic coordinates. Low-$z$ and high-$z$ GRBs are denoted by black and red dots with 1σ error bars, respectively. The lines stand for the best-fit results. Besides, the 1σ and 2σ contours in the $(a, b)$ plane for low-$z$ (black curves) and high-$z$ (red curves) GRBs are plotted in Figure 2. The best-fit central values are denoted by dots.

From Table 2 and Figure 1, we can see that the slope and intercept of low-$z$ GRBs differ from that of high-$z$ GRBs significantly. Low-$z$ GRBs have larger slope, but smaller intercept than high-$z$ GRBs. This can be seen more clearly from the contour plot in the $(a, b)$ plane in Figure 2. There is no overlap between 1σ contours, while only a little overlap between 2σ contours. The best-fit central values of low-$z$ GRBs do not locate in the 3σ contour of high-$z$ GRBs. Similarly, the best-fit...
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central values of high-z GRBs locate outside of the 3σ contour of low-z GRBs. This means that the Amati relation of low-z GRBs differs from that of high-z GRBs at more than 3σ confidence level. Another interesting feature is that, there seems to be a positive correlation between the slope and intercept for low-z GRBs. While for high-z GRBs, the slope is negatively correlated to the intercept. We can also see that the Amati relation is insensitive to cosmological models.

4 DISCUSSIONS AND CONCLUSIONS

In this paper, we investigated the Amati relation for low-z and high-z GRBs separately in three cosmological models, i.e., ΛCDM model, wCDM model and CPL model. SNe Ia were used to constrain the parameters of background cosmos. It was found that the Amati relation of low-z GRBs differs from that of high-z GRBs at more than 3σ confidence level. We noted that the slope of low-z GRB is larger than that of high-z GRBs, while high-z GRBs have larger intercept than low-z GRBs. Our results are consistent with that of Wang, Qi & Dai (2011). We also found a positive correlation between the slope and intercept for low-z GRBs. While for high-z GRBs, the correlation is negative. These features do not depend on the cosmological models.

The Amati relation is often used to calibrate the distance moduli of GRBs. These calibrating methods are based on the assumption that the Amati relation is universal over all redshifts. The redshift-dependence of Amati relation, as indicated in this paper, puts a challenge on this assumption. However, this does not necessarily mean that the Amati relation indeed varies with redshift. Another possibility is that the high-z Hubble diagram deviates from the low-z Hubble diagram predicted by SNe Ia. But this is less likely, because the constraints on the Hubble diagram from the combination of SNe Ia and GRBs (which are calibrated using the Amati relation) is very close to that from SNe Ia alone (Liu & Wei 2014).

The Amati relation has intrinsic scatter much larger than the measurement errors. The uncertainties of distance moduli of GRBs calibrated through Amati relation is about one order of magnitude larger than the uncertainties of SNe Ia (Liu & Wei 2014). When combining GRBs with SNe Ia to constrain cosmological parameters, the weight of GRBs is about two orders of magnitude smaller than that of SNe Ia, since the weight of a data point is inversely proportional to the square of its uncertainty (see Eq.6). This is one reason why adding GRBs to the Union2.1 dataset (or any other datasets which have much higher precision than GRBs) has only small effect on constraining the cosmological parameters (Liu & Wei 2014). Another reason is that the number of GRBs is much smaller than the number of SNe Ia. In addition, use GRBs alone to constrain the cosmological parameters will lead to unreasonable results. All of these arouse us to search for other calibrating methods. The uncertainties should be much reduced before GRBs can be used, in combination with other candles, to trace the Hubble diagram of the Universe.

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