Calibration of Gamma-Ray Burst Luminosity Indicators

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ABSTRACT

Several gamma-ray burst (GRB) luminosity indicators have been proposed, which can be generally written in the form of $L = c \prod x_i^{a_i}$, where $c$ is the coefficient, $x_i$ is the $i$-th observable, and $a_i$ is its corresponding power-law index. Unlike Type-Ia supernovae, calibration of GRB luminosity indicators using a low-redshift sample is difficult. This is because the GRB rate drops rapidly at low redshifts, and some nearby GRBs may be different from their cosmological brethren. Calibrating the standard candles using GRBs in a narrow redshift range ($\Delta z$) near a fiducial redshift has been proposed recently. Here we elaborate such a possibility and propose to calibrate the indices $\{a_i\}$ based on the Bayesian theory and to marginalize the $c$ value over a reasonable range of cosmological parameters. We take our newly discovered multi-variable GRB luminosity indicator, $E_{\text{iso}} = cE_{\gamma,jet}^{a_1} t_{\text{b}}^{a_2}$, as an example and test the validity of this approach through simulations. We show that while $c$ strongly depends on the cosmological parameters, neither $a_1$ nor $a_2$ does as long as $\Delta z$ is small enough. The selection of $\Delta z$ for a particular GRB sample could be judged according to the size and the observational uncertainty of the sample. There is no preferable redshift to perform the calibration of the indices $\{a_i\}$, while a lower redshift is preferable for $c$-marginalization. The best strategy would be to collect GRBs within a narrow redshift bin around a fiducial intermediate redshift (e.g., $z_c \sim 1$ or $z_c \sim 2$), since the observed GRB redshift distribution is found to peak around this range. Our simulation suggests that with the current observational precision of measuring GRB isotropic energy ($E_{\text{iso}}$), spectral break energy ($E_{\gamma}$), and the optical temporal break time ($t_{\text{b}}$), 25 GRBs within a redshift bin of $\Delta z \sim 0.30$ would give fine calibration to the Liang-Zhang luminosity indicator.

Key words: cosmological parameters — cosmology: observations — gamma-rays: bursts

1 INTRODUCTION

The cosmological nature (Metzger et al. 1997) of long gamma-ray bursts (GRBs) and their association with star formation (e.g., Totani 1997; Paczynski 1998; Bromm & Loeb 2002) make GRBs a new probe of cosmology and galaxy evolution (e.g. Djorgovski et al. 2003). Gamma-ray photons with energy from tens of keV to MeV from GRBs are almost immune to dust extinction, and should be detectable out to a very high redshift (Lamb & Reichart 2000; Ciardi & Loeb 2000; Gou et al. 2004; Lin et al. 2004). Several plausible GRB luminosity indicators have been proposed, including luminosity-variability relation (Fenimore & Ramirez-Ruiz 2000; Reichart et al. 2001), luminosity-spectral lag relation (Norris, Marani, & Bonnell 2000), standard gamma-ray jet energy ($E_{\gamma,jet}$) (Frail et al. 2001; Bloom et al. 2003), isotropic gamma-ray energy ($E_{\text{iso}}$) - peak spectral energy ($E_{\gamma}$) relation (Amati et al. 2002), and the break time of the optical afterglow light curves ($t_{\text{b}}$) (Liang & Zhang 2005). Attempts to use these luminosity indicators to constrain cosmological parameters have been made (e.g. Schaefer 2003; Bloom et al. 2003; Dai, Liang, & Xu et al. 2004; Ghirlanda et al. 2004; Friedmann & Bloom 2005; Firmani et al. 2005; Liang & Zhang 2005; Xu, Dai, & Liang 2005; Xu 2005; Mortsell & Sollerman 2005; Wang & Dai 2006). With the discovery of the tight Ghirlanda-relation (Ghirlanda et al. 2004a) and the more empirical LZ-relation (Liang & Zhang 2005), it is now highly expected that GRBs may become a promising standard candle to extend the traditional Type-Ia SN standard candle to higher redshifts (e.g. Lamb et al. 2005).

In order to achieve a cosmology-independent standard candle, one needs to calibrate any luminosity indicator. Otherwise, one inevitably encounters the so-called “circularity problem” (e.g. Firmani et al. 2004; Xu et al. 2005 for dis-
In the case of Supernova cosmology, calibration is
carried out with a sample of Type-Ia SNe at very low red-
shift so that the brightnesses of the SNe are essentially in-
dependent on the cosmology parameters (e.g., Phillips 1993;
Riess et al. 1995). In the case of GRBs, however, this is very
difficult. The observed long-GRB rate falls off rapidly at
low redshifts, as is expected if long-GRBs follow global star
formation. Furthermore, some nearby GRBs may be intrin-
sically different. Observations of GRB 980425, GRB 031203
and other nearby GRBs indicate that they differ from
typical GRBs by showing low isotropic energy, simple light
curve, large spectral lag and dimmer afterglow flux (e.g.,
Norris 2002; Soderberg et al. 2004; Guetta et al. 2004; Liang
& Zhang 2006). Although some GRBs in the optically-dim
sample of Liang & Zhang (2006) still follow the Ghirlanda-
relation and also likely the outliers of the Amati-
relation. If at least some low-redshift GRBs are
980425 and GRB 031203) are clearly outliers of the Amati-
hypothetical relation. If at least some low-redshift GRBs are
different from their cosmological brethren, it is very difficult
to calibrate the GRB standard candle using a low-redshift
sample.

Recently the possibility of calibrating the standard can-
dles using GRBs in a narrow redshift range (Δz) near a fidu-
cial redshift has been proposed (Lamb et al. 2005; Ghirlanda
et al. 2005)\(^1\). In this paper we elaborate this method (Lamb
et al. 2005; Ghirlanda et al. 2005) further based on the
Bayesian theory. We propose a detailed procedure to calib-
rate \(\{a_i\}\) with a sample of GRBs in a narrow redshift
range (Δz) without introducing a low-redshift GRB sample
and marginalize the c value over a reasonable range of cos-
mological parameters. The method is described in §2.
We take our newly discovered GRB luminosity indicator as an
example to test the approach through simulations (§3). The
results are summarized in §4 with some discussion.

2 CALIBRATION METHOD

A GRB luminosity indicator can be generally written in the form of
\[ \hat{L}(\Omega) = c(\Omega)Q(\Omega|X; A), \]

(1)

where \(c(\Omega)\) is the coefficient, \(\Omega\) is a set of cosmological
parameters, and \(Q(\Omega|X; A)\) is a model of the observables
\(X = \{x_i\}\) (measured in the cosmological proper rest frame)
with the parameter set \(A = \{a_i\}\), which is generally written
in the form of \(Q(\Omega|X; A) = \prod x_i^{a_i}\). Since in GRB luminosity
indicators the parameters \(\{x_i\}\) are usually direct ob-
serves (e.g., \(E_p, t_b\), etc.) that only depend on \(z\) but not on
the cosmological parameters, the above expression naturally
separates the \(\Omega\)-dependent part, \(c(\Omega)\), from the \(\Omega\)-insensitive
part, \(Q(\Omega|X; A)\). This allows us to develop an approach to
partially calibrate the luminosity indicators without requiring
a low-redshift GRB sample. Our approach is based on the
Bayesian theory, which is a method of predicting the future
based on what one knows about the past. Our cali-
bration process can be described as follows.

(1) Calibrate \(A\) using a sample of GRBs that satisfy
a luminosity indicator and are distributed in a narrow red-
shift range \(z_0 \in z, \pm \Delta z\). Luminosity distance as a function
of redshift is non-linear, and the dependence of the luminos-
ity distance on the cosmology model at different redshift is
different. Such a sample reduces this non-linear effect. The
parameter set \(A\) can be then derived by using a multiple
regression method in a given cosmology \(\bar{\Omega}, A(\bar{\Omega}, z_0)\).
The goodness of the regression is measured by \(\chi^2_{\min}(\bar{\Omega}, z_0)\),
\[ \chi^2_{\min}(\bar{\Omega}, z_0) = \sum \frac{[\log \hat{L}(\bar{\Omega}, z_0) - \log L(\bar{\Omega}, z_0)]^2}{\sigma_{\log L}(\bar{\Omega}, z_0)}, \]

(2)

where \(N\) is the size of the sample, \(\sigma_{\log L(\bar{\Omega}, z_0)}\) is the error of
the empirical luminosity from the observational errors of
observables, and \(\log L(\bar{\Omega}, z_0)\) is the theoretical luminosity.
The smaller the reduced \(\chi^2_{\min}(\bar{\Omega}, z_0)\), the better the regres-
sion, and hence, the higher the probability that \(A(\bar{\Omega}, z_0)\) is
intrinsic. Assuming that the \(\chi^2_{\min}(\bar{\Omega}, z_0)\) follows a normal
distribution, the probability can be calculated by
\[ P(\bar{\Omega}, z_0) \propto e^{-\chi^2_{\min}(\bar{\Omega}, z_0)/2}. \]

(3)

The calibrated \(A\) with a sample distributed around \(z_0\) is
derived by
\[ A_0 = \frac{\int_{\Omega} A(\Omega, z_0)P(\Omega, z_0)d\Omega}{\int_{\Omega} P(\Omega, z_0)d\Omega}, \]

(4)

and its root mean square (rms) could be estimated by
\[ \delta A_0^2 = \frac{\int_{\Omega} (A(\Omega, z_0) - A_0)^2P(\Omega, z_0)d\Omega}{\int_{\Omega} P(\Omega, z_0)d\Omega}. \]

(5)

where \(\delta A_0(z_0)\) is the unweighted mean of \(A(\bar{\Omega}, z_0)\) in different
\(\bar{\Omega}\).

(2) Marginalize the \(c\) value over a reasonable range for
given GRB sample. The \(c\) value depends strongly on the
cosmological parameters, so it can only be calibrated with a
low redshift sample. Because of the reasons discussed above,
such a low-\(z\) sample is hard to collect. We therefore do not
thesize the \(c\) value but rather marginalize it over a reasona-
range of cosmological parameters for a given GRB
sample. For a given \(c\) one can derive an empirical lumino-
sity \(\hat{L}(\Omega, c, A_0, z_0)\) from the luminosity indicator and its
error. The \(\chi^2(\Omega, c, A_0, z_0)\) and the corresponding probability
\(P(\Omega, c, A_0, z_0)\) can be then calculated with the formulae
similar to Eqs. (2) and (3), respectively. Therefore, the
calibrated luminosity is derived by
\[ \hat{L}_0 = \frac{\int_c \int_{\Omega} \hat{L}(\Omega, c, A_0, z_0)P(\Omega, c, A_0, z_0)d\Omega dc}{\int_{\Omega} \int_c P(\Omega, c, A_0, z_0)d\Omega dc}, \]

(6)

and its rms is estimated by
\[ \delta \hat{L}_0^2 = \frac{\int_c \int_{\Omega} [\hat{L}(\Omega, c, A_0, z_0) - \hat{L}(z_0)]^2P(\Omega, c, A_0, z_0)d\Omega dc}{\int_{\Omega} \int_c P(\Omega, c, A_0, z_0)d\Omega dc}. \]

(7)

where \(\hat{L}(z_0)\) is the unweighted mean of \(\hat{L}_0(\bar{\Omega}, c, A_0, z_0)\) in
different \(c\) and \(\bar{\Omega}\) values.

3 SIMULATION TESTS

The current GRB samples that favor various luminosity indi-
cators are very small, so that one cannot directly utilize our

\(^1\) The similar idea was also discussed in an earlier version of Liang
& Zhang (2005).
approach to perform the calibration. The calibrations would nonetheless become possible in the future when enough data are accumulated. We therefore simulate a large sample of GRBs to examine our approach. The simulations aim to address the questions such as how many bursts are needed, and how narrow the redshift bin should be used, etc., given a particular observed sample. We take the LZ-relation (Liang & Zhang 2005) as an example, which reads

\[ E_{\gamma,iso} = c E_p^{a_1} t_b^{x_2}, \tag{8} \]

where \( t_b \) and \( E_p \) are measured in the cosmic rest frame of the burst proper. We simulate \( 10^6 \) GRBs. Each simulated GRB is characterized by a set of parameters denoted by \( (z, E_p, E_{iso}, t_b) \). It is well known that the \( E_p \) distribution of a bright BATSE GRBs presented by Preece et al. (2000) is well modelled by a Gaussian function. The HETE-2 and Swift observations of X-ray rich GRBs and X-ray flashes (XRFs; Heise et al. 2000; Lamb, Donaghy, & Graziani 2005) have considerably extend the \( E_p \) distribution to a softer band. Liang & Dai (2004) studied the observed \( E_p \) distribution of GRBs and XRFs, combined with both HETE-2 and BATSE observations, and found that the observed \( E_p \) distribution for GRBs/XRFs is bimodal with peaks at \( \sim 30 \) keV and \( \sim 200 \) keV. The \( \sim 30 \) keV peak has a sharp cutoff at the low energy end, likely being due to the instrument threshold limit. A recent study of a Swift burst sample marginally reveals such a bimodal distribution (Zhang et al. 2006). We therefore model the \( E_p \) distribution by combining the observations of BATSE and Swift, i.e.

\[ \frac{dp}{d \log E_p} = \frac{0.70}{0.56 \pi^{1/2}} \exp\left[-2 \left( \frac{\log E_p - 2.30}{0.56} \right)^2\right] \tag{9} \]

\[ + \frac{0.30}{0.56 \pi^{1/2}} \exp\left[-2 \left( \frac{\log E_p - 1.55}{0.56} \right)^2\right] \tag{10} \]

with a cutoff at \( E_p = 30 \) keV (see Fig. 1). The \( E_{iso} \) distribution is obtained from the current sample of GRBs with known redshifts. Since the \( E_{iso} \) distribution suffers observational bias at the low \( E_{iso} \) end, we consider only those bursts with \( E_{iso} > 10^{41.5} \) ergs, and get \( \frac{dp}{d \log E_{iso}} \propto -0.3 \log E_{iso} \). The redshift distribution is assumed following the global star forming history of the universe. The model SF2 of Porciani & Madau (2001) is used. We truncate the redshift distribution at 10. A fluence threshold of \( S_r = 10^{-7} \) erg cm\(^{-2}\) is adopted.

We assume that these GRBs satisfy the LZ-relation and derive \( t_b \) from the simulated \( E_{iso} \) and \( E_p \). Since the observed \( t_b \) is in the range of 0.4 \( - 6 \) days, we also require that \( t_b \) is in the same range to account for the selection effect to measure an optical lightcurve break. Since the observed \( \sigma_x / x \) is about 10% \( - 20\% \), the simulated errors of these observables are assigned as \( \sigma_x / x = 0.25 k \) with a lower limit of \( \sigma_x / x > 5\% \). where \( x \) is one of the observables \( E_p, S_r, \) and \( t_b \), and \( k \) is a random number between 0 \( - 1 \). Our simulation procedure is the same as that presented in Liang & Zhang (2005).

With the simulated GRB sample we examine the plausibility of our calibration approach. We consider only a flat universe with a varying \( \Omega_M \). We picked up two samples with 100 GRBs in each group\(^2\). The first group has a narrow redshift bin (i.e. \( z = 2.0 \pm 0.05 \)) and the second group has a wide redshift bin (i.e. \( z = 2.0 \pm 1.0 \)). We then derive the parameters \( c, a_1, \) and \( a_2 \) using the multivariable regression analysis (Liang & Zhang 2005) for different cosmological parameters \( (\Omega_M) \) and evaluate the dependences of the derived parameters on \( \Omega_M \). The dependences of these quantities on \( \Omega_M \) are quantified by the Spearman correlation, and the results are presented in Figure 2. It is found that \( c \) strongly depends on \( \Omega_M \) regardless of the value of \( \Delta z \), as is expected. On the other hand, while \( a_1 \) and \( a_2 \) are strongly correlated with \( \Omega \) for the case of \( \Delta z = 1.0 \), they are essentially independent of \( \Omega_M \) for \( \Delta z = 0.05 \). These results suggest that once \( \Delta z \) is small enough the influence of cosmological parameters on both \( a_1 \) and \( a_2 \) becomes significant lower than the observational uncertainty and the statistical fluctuation. This makes the calibration of both \( a_1 \) and \( a_2 \) possible with a GRB sample within a narrow redshift bin.

The selection of \( \Delta z \) is essential to most optimally establish the calibration sample. Two effects are needed to take into consideration to select \( \Delta z \), i.e. the observational errors of the sample and the statistical fluctuation effect. The most optimal calibration sample requires that the variations of the standard-candle parameters caused by varying cosmology should be comparable to the variations caused by these two effects. In such a case we could establish a sample with a large enough \( N \) to reduce the fluctuation effect while in the mean time with a small enough \( \Delta z \) so that the dependences of both \( a_1 \) and \( a_2 \) on \( \Omega_M \) are not dominant. Since the relation between \( a_1 \) (or \( a_2 \)) and \( \log \Omega_M \) is roughly fitted by a linear function (see Figure 2), we measure the dependence by the chance probability \( (P) \) of the Spearman correlation. If \( P < 10^{-4} \) the dependence is statistical significant, and the sample is inappropriate for the calibration purpose. Figure 3 shows the distributions of \( \log P \) for \( a_1 \) (left) and \( a_2 \) (right) in the \( \Delta z-N \) plane, assuming the current observational errors for the observables. The grey contours mark the areas where the dependences of \( a_1 \) and \( a_2 \) on \( \Omega_M \) are statistical significant. We find that \( P \) dramatically decreases as \( \Delta z \) increases for a given \( N \). Given a \( P \) value, \( \Delta z \) initially decreases rapidly as \( N \) increases but flattens at \( N > 50 \). This indicates that the statistical fluctuation effect is much lower than the observational errors for a sample with \( N > 50 \). We can see that with the current observational precision, \( \Delta z \sim 0.3 \) is robust enough to calibrate both \( a_1 \) and \( a_2 \). Increasing the GRB sample size alone does not improve the calibration when \( N > 50 \), since the \( a_1 \) and \( a_2 \) errors are dominated by the observational uncertainties in the data. In order to improve calibration further, higher observational precision of \( E_{iso}, E_p, \) and \( t_b \) is needed, which requires a broad-band \( \gamma \)-ray detector and good temporal coverage of the afterglow observations.

The observed GRB redshift distribution ranges from \( 0.0085 \) to \( 6.3 \). We examine if there exists a preferable redshift range for the calibration purpose. We randomly select a sample of 25 GRBs at \( z = \pm 0.3 \), and perform the multivariable regression analysis to derived \( a_1 \) and \( a_2 \) from this sample by assuming a flat universe with \( \Omega_M = 0.28 \). The

\(^2\) Our simulations do not sensitively depend on the \( E_{iso} \) distribution. We have used a random distribution between \( 10^{41.5} \sim 10^{44.5} \) ergs, and found that the characteristics of our simulated GRBs are not significantly changed.

\(^3\) To avoid the statistical fluctuation effect we use a large sample.
The observed $E_p$ distribution: dashed line — derived from bright GRB sample (Preece et al. 2000); step-line — Swift data (Zhang et al. 2006); smoothed curve — our model with bimodal Gaussian distribution (Eq. 9). The dark region marks the cutoff at $E_p < 30$ keV due to the instrument threshold limit.

Figure 1. The observed $E_p$ distribution: dashed line — derived from bright GRB sample (Preece et al. 2000); step-line — Swift data (Zhang et al. 2006); smoothed curve — our model with bimodal Gaussian distribution (Eq. 9). The dark region marks the cutoff at $E_p < 30$ keV due to the instrument threshold limit.

derived $a_1$ and $a_2$ are plotted as a function of $z_c$ in Figure 4. We find that they are not correlated with $z_c$, and their variations are essentially unchanged, i.e. $\sim 0.15$. This indicates that there is no evidence for a vantage redshift range to calibrate $a_1$ and $a_2$. It is therefore equivalent to select a sample at any redshift bin to calibrate $a_1$ and $a_2$. Such a sample is likely to be established with GRBs at $z_c = (1 - 2.5)$, since the observed redshift distribution peaks in this range. The cosmological dependence is less significant at lower redshifts. So, a lower redshift (e.g. $z_c = 1$) sample is preferred for $c$ marginalization.

According to Figure 3, the best strategy to perform GRB standard candle calibration is to establish a moderate GRB sample (e.g. 25 bursts) within a redshift bin of $\Delta z \sim 0.3$ at a fiducial intermediate redshift (e.g. $z_c \sim 1$ or $z_c \sim 2$). We simulate a sample of GRB with $N = 25$, $z = 1 \pm 0.3$, and derive $a_1$ and $a_2$ as a function of $\Omega_M$ in Figure 5. The calibrated $a_1$ and $a_2$ are $1.93 \pm 0.07$ and $-1.23 \pm 0.07$, respectively, where the quoted errors are at 3σ significance level.

4 CONCLUSIONS AND DISCUSSION

We have explored in detail an approach to calibrate the GRB luminosity indicators, $L(\Omega) = c(\Omega) Q(\Omega; X; A)$, based on the Bayesian theory without a low redshift GRB sample. The essential points of our approach include, (1) calibrate $A$ with a sample of GRBs in a narrow redshift bin $\Delta z$; and (2) marginalize the $c$ value over a reasonable range of cosmological parameters for a given GRB sample. We take our newly discovered multi-variable GRB luminosity indicator $E_{iso} = cE_{p0}^{a1}t_b^{a2}$ (LZ-relation) as an example to test the above approach through simulations. We show that while $c$ strongly depends on cosmological parameters, both $a_1$ and $a_2$ do not if $\Delta z$ is small enough. The selection of $\Delta z$ depends on the size and the observational uncertainty of the sample. For the current observational precision, we find $\Delta z \sim 0.3$ is adequate to perform the calibration.

It is also found that the calibrations for both $a_1$ and $a_2$ are equivalent for samples at any redshift bin. The best strategy would be to collect GRBs within a narrow redshift bin around a fiducial intermediate redshift (e.g. $z_c \sim 1$ or $z_c \sim 2$), since the observed GRB redshift distribution is found to peak in this range. Our simulation suggests that with the current observational precision of measuring GRB isotropic energy ($E_{iso}$), spectral break energy ($E_p$), and the optical temporal break time ($t_b$), 25 GRBs within a redshift bin of $\Delta z \sim 0.30$ would give fine calibrations to the LZ-relation. Inspecting the current GRB sample that satisfies the LZ-relation, we find that nine GRBs, i.e. 970828 ($z = 0.9578$), 980703 ($z = 0.966$), 990705 ($z = 0.8424$), 991216 ($z = 1.02$), 020405 ($z = 0.69$), 020813 ($z = 1.25$), 021211 ($z = 1.006$), 041006 ($z = 0.716$), and 050408 ($z = 1.24$) are

Figure 2. Comparison of the dependences of $c$, $a_1$, and $a_2$ on $\Omega_M$ for a sample of 100 GRBs distributed in $z = 2.0 \pm 1.0$ (left panels) and in $z = 2.00 \pm 0.05$ (right panels), respectively. Current observational errors are introduced for the simulated bursts. The dependences are measured by the Spearman correlation, and the correlation coefficient ($r$) and its chance probability ($P$) are marked in each panel.

Figure 3. Distribution of log $P$ in the $(N, \Delta z)$-plane. The grey contours mark the areas where the dependences of $a_1$ and $a_2$ on $\Omega_M$ are statistically significant ($P < 10^{-4}$). The white region is suitable for the calibration purpose.
The calibration sample consists of 25 simulated GRBs at $z_c = 0.3$. The variations of $a_1$ and $a_2$ as a function of $z_c$. The calibration sample consists of 25 simulated GRBs distributed in the redshift bin $z = 1 \pm 0.3$. The dashed lines enclose the $3\sigma$ significance regions.

roughly distributed in the redshift range $z = 1.0 \pm 0.3$. We expect roughly 15 more bursts to form an adequate sample to calibrate the $LZ$-relation.

The observed redshift distribution for the current long GRB sample covers from 0.0085 to 6.29. There have been suggestions that GRB properties may evolve with redshift (e.g. Lloyd-Ronning et al. 2002; Amati et al. 2002; Wei & Gao 2003; Graziani et al. 2004; Yonetoku et al. 2004).

Among the proposed GRB luminosity indicators the cosmological evolution effect has not been considered. With the current GRB sample with known redshifts, it is difficult to access whether and how GRBs evolve with redshift. Nonetheless, since our calibration approach makes use of a GRB sample in a narrow redshift bin, the evolution effect essentially does not affect on the calibration of the parameter set $A$, the set of the power index (indices) in the luminosity indicators. However, it could significantly impact on the $c$-marginalization.

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