Are Gamma-Ray Bursts Standard Candles?

Li-Xin Li
Max-Planck-Institut für Astrophysik, 85741 Garching, Germany

Abstract

By dividing a sample of 48 long-duration gamma-ray bursts (GRBs) into four groups with redshift from low to high and fitting each group with the Amati relation \( \log E_{\text{iso}} = a + b \log E_{\text{peak}} \), I find that parameters \( a \) and \( b \) vary with the mean redshift of the GRBs in each group systematically and significantly. The results suggest that GRBs evolve strongly with the cosmic redshift and hence are not standard candles.

Key words: cosmology: theory – gamma-rays: bursts – gamma-rays: observations.

A remarkable achievement in the observation of GRBs has been the identification of several good correlations among GRB observables [see Schaefer (2007) for a review]. Based on several of those correlations, some people have eagerly proposed that GRBs are standard candles and can be used to probe cosmology to very high redshift through the Hubble diagram [Schaefer, 2003; Dai et al., 2004; Ghirlanda et al., 2004; Lamb et al., 2005; Firmani et al., 2006]. Type Ia supernovae (SNe Ia) have been considered as standard candles and applied to cosmology, which has produced a persuasive evidence that the Universe is currently expanding with an accelerating speed [Clocchiatti, 2006, and references therein].

However, the situation of GRBs is very different from that of SNe Ia. The majority of the observed SNe Ia have redshift \( z \lesssim 0.1 \), so the evolution of SNe Ia plays a minor role. While for GRBs, all the correlations have been obtained by fitting a hybrid GRB sample with redshift spanning a very large range: from \( z \sim 0.1 \) up to \( z \sim 6 \). For objects in such a large range of redshift, it is hard to believe that evolution is not important.

In addition, the physics of SNe Ia is much better understood than that of GRBs. We know that SNe Ia are produced by the thermal nuclear explosion of white dwarfs. For GRBs we are not aware of their progenitors, although many people think that long-duration GRBs arise from the core-collapse of rapidly rotating massive stars [Piran, 2004, and references therein].
The fact that people use a hybrid GRB sample to do statistics without discriminating the redshift distribution is of course caused by the fact that we do not have an enough number of GRBs with measured redshifts limited in a small range. Then, inevitably, the effect of the GRB evolution with redshift, and the selection effects, have been ignored. This raises an important question about whether the relations that people have found reflect the true physics of GRBs or they are superficial (Band & Preece, 2005).

A necessary condition for a class of objects to be standard candles is that they do not evolve with the cosmic redshift. Or, they evolve with the redshift but we know how they evolve (V. Petrosian, this proceeding). For GRBs, neither of these conditions is satisfied.

I use the Amati relation as an example to test the cosmic evolution of GRBs. The Amati relation is a correlation between the isotropic-equivalent energy of long GRBs and the peak energy of their integrated spectra in the GRB frame (Amati et al., 2002)

\[
\log E_{\text{iso}} = a + b \log E_{\text{peak}} .
\]  

With 41 long GRBs with firmly determined redshifts and peak spectral energy, Amati (2006a) has obtained that \(a = -3.35\) and \(b = 1.75\) with the least squares method (\(E_{\text{peak}}\) in keV and \(E_{\text{iso}}\) in \(10^{52}\) erg).

If GRBs do not evolve with the cosmic redshift, we would expect that the Amati relation in equation (1) does not change with the redshift. Hence, a test on the variation of the Amati relation with the redshift could provide some constraint on the cosmic evolution of GRBs.

For this purpose, I separate a sample of 48 long GRBs [41 GRBs from Amati (2006a), and seven additional Swift GRBs from Amati (2006b)] into four groups by the redshift, each group containing 12 GRBs:

- **Group A** – 0.1 < \(z\) < 0.84, \(\langle z \rangle = 0.56\);
- **Group B** – 0.84 ≤ \(z\) < 1.3, \(\langle z \rangle = 1.02\);
- **Group C** – 1.3 ≤ \(z\) < 2.3, \(\langle z \rangle = 1.76\);
- **Group D** – 2.3 ≤ \(z\) ≤ 5.6, \(\langle z \rangle = 3.40\); where \(\langle z \rangle\) is the mean redshift.

Then, I fit each group by equation (1) and calculate the mean redshift, and check if the values of \(a\) and \(b\) evolve with the redshift. The results are shown in Fig. 1 (left panel; \(\Omega_m = 0.3\), \(\Omega_A = 0.7\), and \(H_0 = 70\) km s\(^{-1}\) Mpc\(^{-1}\)).

A least squares fit to the 48 GRBs as a single sample with equation (1) leads to \(a = -3.42\) and \(b = 1.78\), with the reduced \(\chi^2 = 5.9\). The results are consistent with that obtained with 41 GRBs by Amati (2006a). In the right panel of Fig. 1, I plot the deviation of fit \([s; \text{see Li & Paczyński (2006)}]\) against the mean redshift of GRBs. There is not a clear trend for \(s\) to vary with \(\langle z \rangle\). But
Fig. 1. Left panel: Least squares fit to each of the four groups of GRBs by equation (1) (solid line). The two dashed lines mark the 1-σ deviation of the fit. Right panel: The deviation of fit. Each circle corresponds to a group of GRBs. The star ($s = 0.16$) is the result obtained by fitting the whole sample (48 GRBs).

Fig. 2. The fitted value of $a$ (left panel) and $b$ (right panel) against the mean redshift of GRBs. Each data point with error bars represents a group of GRBs. The solid line is a least squares linear fit to $a—\langle z \rangle$ and $b—\langle z \rangle$.

it appears that the deviation of fit of each group is smaller than that of the whole sample. This fact indicates that treating GRBs at different redshifts as a single sample may increase the data dispersion.

I find that the values of $a$ and $b$ vary with the mean redshift of the GRBs monotonically. In Fig. 2, I plot $a$ and $b$ against $\langle z \rangle$. Clearly, $a$ and $b$ are correlated/anti-correlated with $\langle z \rangle$. The Pearson linear correlation coefficient between $a$ and $\langle z \rangle$ is $r(a, \langle z \rangle) = 0.975$, corresponding to a probability $P = 0.025$ for a zero correlation. The correlation coefficient between $b$ and $\langle z \rangle$ is $r(b, \langle z \rangle) = -0.960$, corresponding to $P = 0.040$ for a zero correlation.
A least squares linear fit to $a-\langle z \rangle$ leads to

$$a = -4.58 + 0.43 z,$$  \hspace{1cm} (2)

with $\chi^2_r = 0.13$. A least squares linear fit to $b-\langle z \rangle$ leads to

$$b = 2.32 - 0.207 z,$$  \hspace{1cm} (3)

with $\chi^2_r = 0.31$.

The results indicate that $a$ and $b$ strongly evolve with the cosmic redshift.

I have used Monte-Carlo simulations to test if the variation of $a$ and $b$ with the redshift is caused by the selection effect. The results show that there is only a $\sim 4$ percent chance that the observed variation is caused by the selection effect arising from the limit in the GRB fluence \cite{Li2007}. Hence, the variation of the Amati relation with redshift that I have discovered may reflect the cosmic evolution of GRBs and indicates that GRBs are not standard candles.

The results need to be tested with more GRBs. No matter what the conclusion will be (whether the variation of parameters is caused by the GRB evolution or by the selection effect), the results suggest that it is very risky to use GRBs with redshifts spanning a large range as a single sample to analyze physical relations among observables. Although I have only tested the Amati relation, it would be surprising if any of the other relations does not change with redshift.

References

Amati L., 2006a, MNRAS, 372, 233
Amati L., 2006b, arXiv:astro-ph/0611189v2
Amati L. et al., 2002, A&A, 390, 81
Band D., Preece R. D., 2005, ApJ, 627, 319
Clocchiatti A. et al., 2006, ApJ, 642, 1
Dai Z. G. et al., 2004, ApJ, 612, L101
Firmani C. et al., 2006, MNRAS, 372, L28
Ghirlanda G. et al., 2004, ApJ, 613, L13
Lamb D. Q. et al., 2005, arXiv:astro-ph/0507362v1
Li L.-X., 2007, arXiv:0704.3128v1 [astro-ph]
Li L.-X., Paczyński B., 2006, MNRAS, 366, 219
Piran T., 2004, Rev. Mod. Phys., 76, 1143
Schaefer B. E., 2003, ApJ, 583, L67
Schaefer B. E., 2007, ApJ, 660, 16