COSMOLOGICAL TIME DILATION IN DURATIONS OF SWIFT LONG GAMMA-RAY BURSTS

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ABSTRACT

Cosmological time dilation is a fundamental phenomenon in an expanding universe, which stresses that both the duration and wavelength of the emitted light from a distant object at the redshift $z$ will be dilated by a factor of $1 + z$ at the observer. By using a sample of 139 Swift long gamma-ray bursts with known redshift ($z \leq 8.2$), we measure the observed duration ($T_{90}$) in the observed energy range between $140/(1 + z)$ keV and $350/(1 + z)$ keV, corresponding to a fixed energy range of 140–350 keV in the rest frame. We obtain a significant correlation between the duration and the factor $1 + z$, i.e., $T_{90} = 10.5(1 + z)^{0.94 \pm 0.26}$, which is consistent with that expected from the cosmological time dilation effect.

Key words: gamma-ray burst: general – methods: data analysis

Online-only material: color figures

1. INTRODUCTION

Gamma-ray bursts (GRBs) are the most violent explosions in distant galaxies (Piran 2004; Zhang & Mészáros 2004). The search for the cosmological time dilation signature in GRB data, a fundamental phenomenon in an expanding universe, has a long history. In the pre-Swift-era, the verification of the time dilation signature in GRB data was heavily debated (Norris et al. 1994; Che et al. 1997a, 1997b; Lee & Petrosian 1997; Deng & Schaefer 1998; Lee et al. 2000; Mitrofanov et al. 1996; Chang 1994; Che et al. 1997a, 1997b; Lee & Petrosian 1997; Deng & Gao 2003). The main uncertainty of these early results is that these samples contained a small number of or even zero bursts with known redshift. Thanks to the successful performance of the Swift satellite (Gehrels et al. 2004), the number of GRBs with measured redshift has increased rapidly and a reliable test of the time dilation signatures reported in the previous literature becomes possible. Nevertheless, recent analyses have yet to reveal sound evidence for the cosmological time dilation effect in GRBs detected by Swift or the Fermi Gamma-ray Space Telescope (Sakamoto et al. 2011; Kocevski & Petrosian 2013; Gruber et al. 2011).

It is well known that the intrinsic durations or light curves of GRBs are highly energy dependent (Fenimore et al. 1995; Norris et al. 1996; Peng et al. 2006; Zhang et al. 2007; Qin et al. 2013). We note that most previous works ignored this effect and simply measured the observed durations in a fixed observed energy range. As a result, the received photons belong to different energy ranges. Therefore, the observed durations would be strongly biased since they simply recorded different parts of the intrinsic light curves. This can be resolved by choosing a fixed energy range in the rest frame and measuring the observed duration in a projected energy range by the relation $E_{\text{obs}} = E_{\text{rest}}/(1 + z)$, where $E_{\text{obs}}$ and $E_{\text{rest}}$ are the energy of the photon measured in the observer and the rest frame, respectively (Sakamoto et al. 2011; Gruber et al. 2011; Ukwatta et al. 2012). When taking this effect into account, we calculate the observed durations of Swift GRBs with known redshifts within the observed energy band $140/(1 + z)$ keV to $350/(1 + z)$ keV, corresponding to the same rest frame energy range 140–350 keV, and reanalyze the redshift dependence of the durations. We find that there is a significant trend for the inferred duration to be longer in bursts at higher redshifts and the durations are stretched approximately by a factor $(1 + z)$, as expected from the cosmological time dilation effect. We describe our sample and data analysis in Section 2, present the results in Section 3, and give our conclusions in Section 4.

2. SAMPLE AND DATA ANALYSIS

In order to obtain a complete sample and minimize the influence of different instruments (with different sensitivities and energy bands), only Swift GRBs with known redshift are considered. We obtained a sample of 194 bursts with known redshift detected by 2012 March. We downloaded the data from the Swift Archive5. Archive available at ftp://legacy.gsfc.nasa.gov/swift/data/. The time tagged event (TTE) data from the Burst Alert Telescope (BAT) onboard Swift have an excellent time resolution of 100 μs, which can be used to perform the temporal analysis effectively. The standard BAT software (HEASOFT 6.8) and the latest calibration database were used to process the BAT TTE data. We extracted 64 ms (long bursts) or 16 ms (short bursts) binned light curves from the TTE data and determined the GRB duration, $T_{90}$ ($T_{50}$), using the time in which 90% (50%) of the burst counts are collected (Kouveliotou et al. 1993). The widely used Bayesian Block method (Scargle 1998) was adopted to extract the duration value.

Using the standard method described above, we first calculated the values of $T_{90,\text{raw}}$ and $T_{50,\text{raw}}$, where the subscript “raw” represents the data measured in the observer’s energy range of 15–350 keV. These duration values have generally been used in previous studies. But the statistical analysis of $T_{90,\text{raw}}$ and $T_{50,\text{raw}}$ is somehow meaningless or even misleading, because the values of $T_{90,\text{raw}}$ and $T_{50,\text{raw}}$ are highly affected by

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4 http://www.mpe.mpg.de/~jcg/grbgen.html
5 ftp://legacy.gsfc.nasa.gov/swift/data/
both the energy-dependent effect and the cosmological time-dilation effect. By fixing the energy range in the GRB rest frame, the energy-dependent effect is removed. We then created the light curves in the observed energy range 140/(1 + z) – 350/(1 + z) keV. This energy band was chosen so that the projecting energy bands of all Swift GRBs with known redshifts lie in the Swift-BAT observed energy range (15–350 keV). We used the same algorithm to find the best T90 and T30 durations in the observed 140/(1 + z)–350/(1 + z) keV band. The rest frame durations T90,rest and T30,rest can be easily obtained by dividing the observed durations by (1 + z).

In our initial sample of 194 GRBs, some bursts are not bright enough to measure T90 and T30 in the rest frame energy range 140–350 keV. Six super-long/peculiar bursts (GRBs 060124, 060218, 100316D, 101225A, 110328A, 111209A) are excluded in our investigation. In the analysis we also exclude the short duration bursts, including two with extended emission (GRBs 060614 and 061210). Please note the short and long duration bursts ($\lesssim 2$ s) are defined following Kouveliotou et al. (Kouveliotou et al. 1993),$^6$ not by the T90 measured in this work. The benefit of excluding them is to have a sample of GRBs that have an intrinsically same (or similar) duration distribution. Our analysis is thus based on a Swift GRB sample consisting of 139 long GRBs. In addition, three very high redshift candidates (GRBs 090429B, 120521C and 120923A) are also presented for comparison.

3. RELATION BETWEEN DURATION AND REDSHIFT

Assuming that the intrinsic duration of all GRBs is similar, one would expect the observed duration to increase as a function of redshift due to cosmological expansion. As shown in the left panel of Figure 1, there is a clear trend that the more distant bursts tend to have larger T90 and T30. We parameterize the correlation and obtain $\log T90 = (1.02 \pm 0.14) + (0.94 \pm 0.26) \log (1 + z)$, where the Pearson correlation coefficient is $r = 0.29$ and the chance probability is $p = 0.0005$. For T30, we have $\log T30 = (0.58 \pm 0.14) + (1.07 \pm 0.27) \log (1 + z)$ with $r = 0.32$ and $p = 0.0001$. Therefore the observed GRB durations are indeed stretched by approximately a factor of $(1 + z)$, as expected from the cosmological time dilation effect. The scatter is large and, in particular, two very high redshift GRBs (GRBs 080913A at $z = 6.7$ and 090423 at $z = 8.2$) and two high redshift candidates (GRBs 090429B at $z \sim 9.4$ and 120923A at $z \sim 8.5$) do not comply well with the correlation. This might be because the intrinsic duration is not the same for all bursts. Besides, Zhang et al. (2009) have showed that most GRBs with the highest redshifts seem to have rest-frame durations shorter than 2 s, yet still show multi-wavelength properties similar to most long GRBs. Recently, using simulations, several groups found that the diminishing signal-to-noise ratio of higher redshift GRBs makes only the bright narrow portions of the bursts accessible to the detectors (i.e., the so-called “tip-of-the-iceberg” effect), so the measured durations should be considered as lower limits to the true values (Kocevski & Petrosian 2013; Lü et al. 2012; Littlejohns et al. 2013).

To better show the correlation we divided the sample of 139 GRBs into six groups with an almost equal number of bursts. We calculated the mean values of T90, T30 and z in each group and reanalyze their relations. From the right panel of Figure 1 we find that the mean durations ($T_{90,\text{mean}}, T_{30,\text{mean}}$) are tightly correlated with the mean redshift $z_{\text{mean}}$. Fitting the correlation we have $\log T_{90,\text{mean}} = (1.28 \pm 0.10) + (0.97 \pm 0.19) \log (1 + z_{\text{mean}})$ with $r = 0.93$ and $p = 0.007$, and $\log T_{30,\text{mean}} = (0.80 \pm 0.11) + (1.25 \pm 0.20) \log (1 + z_{\text{mean}})$ with $r = 0.95$ and $p = 0.004$. Hence the $(1 + z)$ stretching of durations is established. We have also analyzed the potential influence of the numbers of groups on the statistical result, and found that

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$^6$ Recently, Bromberg et al. (2013) suggested that the commonly used limit of 2 s is conservative and the division $\lesssim 0.8$ is more suitable for Swift.
the slope of the correlation is almost invariable and close to 1 for the different sets of groups. Although the intrinsic durations of individual bursts are very different, their mean value is dilated exactly by a factor of $1 + \frac{z}{r}$ following the nature of the expanding universe (Paczyński 1992; Piran 1992).

Is the observed duration stretching due to the redshift evolution of the intrinsic duration of GRBs? To answer this question, we analyze the distribution of the rest frame duration $T_{90,\text{rest}}$ and $T_{50,\text{rest}}$ as well as the relation between these two quantities and redshift. From the left panel of Figure 2, we find that the distributions of $T_{90,\text{rest}}$ and $T_{50,\text{rest}}$ span a wide range and their log-median values are 10.7 s and 4.6 s, respectively. Obviously, different GRBs do not have a standard intrinsic duration, but the similar median values of the intrinsic duration $T_{90,\text{rest}}$ ~ 10 s have been reported by many authors even though different energy ranges and different instruments have been used (Pélangeton et al. 2008; Shao et al. 2010; Gruber et al. 2011). Therefore, we can only identify the cosmological time dilation as a statistical effect. The right panel of Figure 2 shows the redshift dependence of $T_{90,\text{rest}}$ and $T_{50,\text{rest}}$ and we do not find any evidence of the evolution effect of the rest frame duration, where the correlation coefficients (chance probabilities) between $T_{90,\text{rest}}$ and $T_{50,\text{rest}}$ and the redshifts are $r = -0.02$ ($p = 0.82$) and $r = 0.02$ ($p = 0.79$), respectively. A similar conclusion was also obtained from analyzing the preliminary Fermi/GBM data (Gruber et al. 2011).

It is well known that the duration of GRBs is highly affected by the detector threshold. In order to avoid the influence of the detector threshold on the correlation between duration and redshift, we construct a subsample with relatively bright bursts in the 15–150 keV Swift/BAT band. The subsample is selected with the criteria that the bursts have 1 s peak photon flux $P > 2.6$ ph s$^{-1}$ cm$^{-2}$ as used by Salvaterra et al. (2012), 63 GRBs match our selection criteria. Using this subsample, we analyze the relations between $T_{90}$, $T_{50}$ and $z$ (Figure 3). From Figure 3, we can find that the observed durations are highly dependent on redshift for these bright GRBs, which is consistent with the above result. We parameterize the correlation and obtain $\log T_{90} = (0.87 \pm 0.20) + (1.07 \pm 0.45) \log (1 + z)$ with $r = 0.29$ and $p = 0.02$. For $T_{50}$, we have $\log T_{50} = (0.46 \pm 0.19) + (1.01 \pm 0.42) \log (1 + z)$ with $r = 0.29$ and $p = 0.02$. These results further confirm that the cosmological time dilation effect identified in the duration of GRBs is reliable.

Previous works analyzing the data of Swift GRBs have reported no evidence for the duration being stretched by a factor of $(1 + z)$ (Sakamoto et al. 2011; Kocevski & Petrosian 2011). From Figure 3, we can find that the observed durations are highly dependent on redshift for these bright GRBs, which is consistent with the above result. We parameterize the correlation and obtain $\log T_{90} = (0.87 \pm 0.20) + (1.07 \pm 0.45) \log (1 + z)$ with $r = 0.29$ and $p = 0.02$. For $T_{50}$, we have $\log T_{50} = (0.46 \pm 0.19) + (1.01 \pm 0.42) \log (1 + z)$ with $r = 0.29$ and $p = 0.02$. These results further confirm that the cosmological time dilation effect identified in the duration of GRBs is reliable.

(A color version of this figure is available in the online journal.)
function of redshift (see also Wei & Gao 2003). However, Lü et al. (2013) found that the rest frame duration decreases as a function of redshift, following previous approaches we also investigated the correlations between $T_{90,raw}$, $T_{50,raw}$ and $z$. From the left panel of Figure 4, we find that there is indeed no evidence for the dilation-like effect in the raw duration data, in agreement with that found in previous studies. The respective correlation coefficients between $T_{90,raw}$ and $T_{50,raw}$ and the redshifts are $r = 0.03$ ($p = 0.69$) and $r = 0.13$ ($p = 0.13$). This suggests that the cosmological time dilation effect has been canceled out by the energy-dependent effect of the duration, since the further away the burst is located, the shorter the portion of the light curve (corresponding to a higher energy range in the rest frame) recorded in the observed energy range.

In addition, Pélangeon et al. (2008) and Kocevski & Petrosian (2013) found that the rest frame duration decreases as a function of redshift (see also Wei & Gao 2003). However, it should be noted that in the rest frame duration used in these works, simply dividing the raw duration measured in a fixed detector energy range by a factor of $(1 + z)$, the energy-dependent effect is not considered. As a test, we also calculated $T_{90,raw}/(1+z)$ and $T_{50,raw}/(1+z)$ and analyzed their relations with redshift. As shown in the right panel of Figure 4, both $T_{90,raw}/(1+z)$ and $T_{50,raw}/(1+z)$ all show a decreasing trend with increasing redshift. We parameterize the correlations and obtain $\log(T_{90,raw}/(1+z)) = (1.65 \pm 0.13) + (-0.92 \pm 0.25) \log (1 + z)$ with $r = -0.3$ and $p = 0.0004$, and $\log(T_{50,raw}/(1+z)) = (1.07 \pm 0.14) + (-0.64 \pm 0.27) \log (1 + z)$ with $r = -0.2$ and $p = 0.02$. Hence we have demonstrated that a reliable relation between the duration and the redshift cannot be reliably established if one ignores the energy-dependent effect.

4. SUMMARY AND CONCLUSIONS

In this work we perform a statistical analysis of the duration of a sample of 139 long GRBs with known redshift detected by Swift until 2012 March. We calculated the observed duration ($T_{90}$ and $T_{50}$) of all bursts in the observed energy range 140–350 keV in the rest frame. This actually means that the energy-dependent effect is removed. By analyzing the relation between $T_{90}$, $T_{50}$ and redshift, we find that there is a significant trend for both $T_{90}$ and $T_{50}$ to be longer in bursts at higher redshifts and $T_{90} = 10.5(1 + z)^{0.94 \pm 0.26}$ and $T_{50} = 3.8(1 + z)^{1.07 \pm 0.27}$. Such results are well consistent with those expected from the cosmological time dilation effect that all timescales of GRBs should be stretched by a factor of $(1 + z)$. We also find that the intrinsic duration of GRBs is independent with redshift and its distribution spans a wide range, where the median value of $T_{90,rest}$ ($T_{50,rest}$) is 10.7 s (4.6 s), respectively. If one only uses the raw duration calculated within a fixed detector energy range to make the statistical analysis of duration, the result can be misleading. For example in some literature the “intrinsic duration” is found to be anti-correlated with the redshift, which is at odds with our finding. Hence a reliable relation between the duration and the redshift cannot be reliably established if one ignores the energy-dependent effect of the duration.

We note that the correlation between duration and redshift has a very large scatter, this might be due to the intrinsic scatter of duration. A more important fact is that the several very high redshift GRBs deviate from the correlation. This might be caused by the integrated effect. An more important reason is the “tip-of-the-iceberg” effect, i.e., with increasing redshift and decreasing signal-to-noise ratio only the brightest portion of GRB light curves can be detected, so the measured durations should be considered as lower limits to the true values (Kocevski & Petrosian 2013; Liu et al. 2012; Littlejohns et al. 2013). In addition, the BAT effective area is not uniform, it sharply drops above 100 keV, and below 25 keV (Barthelmy et al. 2005; see also http://swift.gsfc.nasa.gov/analysis/bat_digest.html). This mainly affects the two extremes of the redshift distribution. The durations of low-redshift ($z < 1$) and highest-redshift ($z > 8$) events could therefore be also underestimated.

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