STUDY OF GRB LIGHT-CURVE DECAY INDICES IN THE AFTERGLOW PHASE

Roberta Del Vecchio¹, Maria Giovanna Dainotti¹,²,³, and Michal Ostrowski¹

¹ Astronomical Observatory, Jagiellonian University, ul. Orla 171, 30-244 Kraków, Poland; roberta@oa.uj.edu.pl (RDV), mdainott@stanford.edu (MGD), michal.ostrowski@uj.edu.pl (MO)
² Physics Department, Stanford University, Via Pueblo Mall 382, Stanford, CA, USA
³ INAF-Istituto di Astrofisica Spaziale e Fisica Cosmica, Via Gobetti 101, I-40129, Bologna, Italy

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ABSTRACT

In this work, we study the distribution of temporal power-law decay indices, α, in the gamma-ray burst (GRB) afterglow phase, fitted for 176 GRBs (139 long GRBs, 12 short GRBs with extended emission, and 25 X-ray flashes) with known redshifts. These indices are compared with the temporal decay index, α_w, derived with the light-curve fitting using the Willingale et al. model. This model fitting yields similar distributions of α_w to the fitted α, but for individual bursts a difference can be significant. Analysis of (α, L_a) distribution, where L_a is the characteristic luminosity at the end of the plateau, reveals only a weak correlation of these quantities. However, we discovered a significant regular trend when studying GRB α values along the Dainotti et al. correlation between L_a and the end time of the plateau emission in the rest frame, T_a^*, a hereafter LT correlation. We note a systematic variation of the α parameter distribution with luminosity for any selected T_a^*. We analyze this systematics with respect to the fitted LT correlation line, expecting that the presented trend may allow us to constrain the GRB physical models. We also attempted to use the derived correlation of α(T_a^*) versus L_a(T_a^*) to diminish the luminosity scatter related to the variations of α along the LT distribution, a step forward in the effort of standardizing GRBs. A proposed toy model accounting for this systematics applied to the analyzed GRB distribution results in a slight increase of the LT correlation coefficient.

Key words: distance scale – gamma-ray burst: general

Supporting material: figure set, machine-readable table

1. INTRODUCTION

Gamma-ray bursts (GRBs) with their powerful emission processes are observed up to high redshifts, z > 9 (Cucchiara et al. 2001). A significant progress in studying GRB observations has been the advent of the Swift satellite (Gehrels et al. 2004), which has revealed a more complex behavior of the light curves (Nousek et al. 2006; O’Brien et al. 2006; Zhang et al. 2006; Sakamoto et al. 2007) than in the past. There are several emission models proposed in the literature providing predictions for characteristic GRB light-curve features. Well known is the model of Mezsárös (1998, 2006) and Meszaros & Rees (1999), consisting of jet internal shocks generating the GRB prompt phase emission and external shocks of the GRB expanding fireball generating the afterglow emission.

In the present paper, we study distributions of the GRB afterglow parameters versus light-curve temporal decay indices α, for the power-law decay observed in the afterglow phase, with the X-ray luminosity L_a. We analyze an extended sample of 176 GRBs with known redshifts observed by Swift from 2005 January to 2014 July. In the presented analysis, we use the LT correlation (Dainotti et al. 2008), updated in Dainotti et al. (2010, 2011a, 2013b, 2015b), between the derived characteristic afterglow plateau luminosity, L_a, and time, T_a^* (an index * indicates the GRB rest frame quantity). An attempt to study similar afterglow properties was presented by Gendre et al. (2008). They analyzed the “late” light-curve properties at the time of one day after the burst to reveal the existence of grouping the GRB luminosities into two groups, which also differ in their redshift distributions. In their study they noted relations among some GRB parameters, in particular, a non-trivial distribution of X-ray spectral indices versus the light-curve temporal decay indices, but no dependence of these indices on the GRB luminosity. In addition, prompt-afterglow correlations have been studied by Dainotti et al. (2015a, 2011b), Margutti et al. (2013), and Grupe et al. (2013).

Importance of the present study results also from the fact that the afterglow LT correlation has already been the object of theoretical modeling either via accretion (Kumar et al. 2008; Cannizzo & Gehrels 2009; Lindner et al. 2010; Cannizzo et al. 2011), via a magnetar model (Bernardini et al. 2011; Dall’Oso et al. 2011; Rowlinson & O’Brien 2012; Rowlinson et al. 2013, 2014; Rea et al. 2015) or via energy injection (Sultana et al. 2013; Leventis et al. 2014; van Eerten 2014a, 2014b), and there were attempts to apply it as a cosmological tool (Cardone et al. 2009, 2010; Dainotti et al. 2013a; Postnikov et al. 2014). Here, we extend the LT correlation study looking into its possible dependence on the additional physical parameter α characterizing the afterglow light curve.

Below, in Section 2, we introduce the data set analyzed in this study. In Section 3, we describe the performed observational data analysis and the derived distributions of decay indices α. The analysis reveals a weak correlation for α and L_a, but a significant systematic trend along the correlated (L_a, T_a^*) distribution. In Section 4, we present our final discussion and conclusions. We shortly consider the physical interpretation of the α distribution. Then, we perform a preliminary exploration of a new possibility of using GRBs as cosmological standard candles, illustrated with a proposed toy model involving scaling GRB afterglow luminosity to the selected standard α_w.

The fitted slopes and normalization parameters of the correlations presented in this paper are derived using the D’Agostini (2005) method. The ΛCDM cosmology applied here uses the parameters H_0 = 71 km s^{-1} Mpc^{-1}, Ω_Λ = 0.73, and Ω_M = 0.27.
Below, we analyze the distribution of afterglow light-curve decay indices, $\alpha$, for the data set of 176 GRBs with known redshifts, observed by Swift from 2005 January to 2014 July. Within this sample, we consider separately subsamples of 139 long GRBs, 25 X-Ray Flashes (XRFs)$^4$, and 12 short GRBs with extended emission. The sample of 164 long GRBs and XRFs is also considered together as a single sample.

As described in Dainotti et al. (2013b), all the analyzed light curves were fitted using an analytic functional form proposed by Willingale et al. (2007). The considered sample was chosen from all Swift GRBs with known redshifts by selecting only those events that allowed a reliable afterglow fitting. The fits provided physical parameters for the GRB afterglows, including their characteristic luminosities and time, $L_\alpha$ and $T_\alpha$, at the end of the afterglow plateau phase, and the power-law temporal decay index, $\alpha_W$, for the afterglow decaying phase.$^5$ The fitted indices $\alpha_W$ are influenced by the requirement of the best global light-curve fitting for the considered analytic model. Therefore, we decided to apply a different procedure for the derivation of the temporal decay index $\alpha$ to be used in the following analysis, intended to provide a more accurate fit of the light-curve power-law decay part immediately after the plateau. In each GRB, we selected the afterglow light-curve section with a power law and we performed the $\chi^2$ fitting of $\alpha$ in such a range, as presented in figure set 1 for all GRBs showing the performed fits and providing the fitting parameters in Table 1. We compared these parameters with those by Evans et al. (2009) and the ones quoted in the Swift Burst Analyzer (http://www.swift.ac.uk/burst_analyser/), having nearly the same $\alpha$ values in the majority of cases. However, significant differences are also found in individual cases due to the different time ranges considered for the fits.

The applied procedure allowed us to remove all clear deviations of the power-law from the fitting due to flares and non-uniformities in the observational data. In the case of a break in the decaying part of the light curve, a value of $\alpha$ was fitted to the brighter/earlier part of the light curve. We have to note that in some rare cases it was impossible to decide if the first part of the light curve can be considered the decaying part, or still a steep plateau phase, and the presented fits can be disputed. We decided to use all derived data in the analysis and correlations studied in this paper, leaving the possibility of some particular data selection and/or rejecting some events from the analysis to the future study.

Comparison of the $\alpha$ and $\alpha_W$ distributions in Figure 2 shows that both measured decay indices have similar distributions, but differences for individual fitted values can be

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### Table 1

| GRB    | $\alpha$ | $\alpha_W$ | $T_1$ (s) | $T_2$ (s) | Type      |
|--------|----------|------------|-----------|-----------|-----------|
| 050315 | 1.26     | 0.91       | 4.80      | 6.38      | L         |
| 050318 | 1.28     | 0.91       | 3.50      | 4.50      | L         |
| 050319 | 1.53     | 0.91       | 4.50      | 5.73      | L(XRF)    |
| 050401 | 1.35     | 0.91       | 3.70      | 5.74      | L         |
| 050416A| 0.91     | 0.91       | 3.60      | 6.38      | L(XRF)    |

Note. $T_1$ and $T_2$ are the logarithms of the start and ending times of the fit. The types are $L$ = Long, $S$ = short, and XRF = X-ray flashes. (This table is available in its entirety in machine-readable form.)

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$^4$ XRFs are bursts of high energy emission similar to long GRBs, but with a spectral peak energy one order of magnitude smaller than in the long GRBs and with fluence greater in the X-rays than in the gamma-ray band. Sometimes XRFs are considered to be misaligned long GRBs (Ioka & Nakamura 2001; Yamazaki et al. 2002) and this is why we also analyze both of these samples together.

$^5$ These data are available upon request from M.G. Dainotti.
significant. The parameters of the Gaussian fits for both presented distributions are a mean value $\mu(\alpha) = 1.40$ with standard deviation $\sigma(\alpha) = 0.46$ for our power-law fitting compared to $\mu(\alpha_P) = 1.45$ and $\sigma(\alpha_P) = 0.45$ for the Willingale model fitting. The $P$-value of the T-test between these two distributions is 0.89, indicating no statistically significant differences between the two distributions.

3. ANALYSIS OF THE AFTERGLOW DECAY LIGHT CURVES

By adopting the analyzed subsample of long GRBs+XRFs, systematic trends in the ($\log L_\alpha$, $\alpha$) distribution can be studied. As presented in Figure 3, there is an indication that these quantities are (weakly) correlated. However, the scatter of points around the correlation line is substantial and the derived Spearman (1904) correlation coefficient $\rho = 0.17$ is small. The fitted correlation line is $\log L_\alpha = 0.30 \alpha + 47.20$, showing that on average faster light-curve decay seems to occur for GRBs with higher luminosities. However, here we stress again that the trend is weak in this highly scattered distribution. The same analysis using the long GRBs subsample only leads to a slightly weaker correlation with $\rho = 0.14$ and $P = 10^{-4}$.

It should be noted that the large scatter of the GRB luminosity distribution cannot be due only to the fitting method used for its derivation. Significant contribution to this scatter must result from the very nature of the GRB sources, possibly modified by the explosion geometry.

In an attempt to evaluate the trend in Figure 3, we decided to compare distributions of $\alpha$ plotted for three luminosity ranges with equal numbers of GRBs: a low luminosity range —$\log L_\alpha < 47.25$, a medium range—$47.25 < \log L_\alpha < 48.2$, and a high range—$\log L_\alpha > 48.2$. Normalized cumulative distribution function CDF ($\text{CDF}(x) \equiv \sum_0^x (1/N)$, where summing includes all GRBs with $\alpha < x$ and $N$ is the number of GRBs in the considered sample) approximates the cumulative probability function in the $\alpha$ space. In Figure 4, we present these functions in the three analyzed luminosity ranges for the whole GRB sample, as well as for long GRBs, short GRBs, and XRF subsamples. Comparison of the red and blue CDF distributions presented in Figure 4 convincingly (maybe less convincingly for the short subsample) supports the existence of the ($\log L_\alpha$, $\alpha$) correlation. The same systematics for all analyzed GRB samples with lower luminosity events show the tendency to slower light-curve decay. The most luminous GRBs (blue lines) seem to grow faster to unity with their smaller $\alpha$ scatter. This result is also confirmed by the Kolmogorov–Smirnov (KS) test. The test applied for low (red line) and high (blue line) luminosity GRB distributions along the $\alpha$ coordinate (Figure 5) shows that it is highly unlikely, with $P = 0.01$, that both distributions are drawn randomly from the same population. As regards the XRFs and short GRBs subsamples, the available number of elements is too low for establishing reliable statistical results; however, the distributions of brighter GRBs seem to show the same tendency to be centered at higher $\alpha$ values than the dimmer ones.

There is no well understood universal recipe for differentiating the physical properties of the GRB source from observational data yet, but the existence of $\log L_\alpha$ versus $\log T^*_{\text{obs}}$ correlation reflects the presence of approximately uniformly varying properties of GRB progenitor in the plateau phase. If these properties would be the GRB progenitor mass and/or its angular momentum, then different external medium profiles could be expected around the exploding massive star, where the afterglow related shock propagates. Therefore, it may be expected to detect more clear dependence between the afterglow luminosity and the $\alpha$ index for GRBs analyzed.
within a limited range of $T_a^*$. To proceed, in analogy to the above analysis for selected luminosity ranges, we study relative distributions of GRB subsamples along the LT distribution in three ranges of the decay index: the ”slowly” decaying light curves with $0.53 < \alpha < 1.23$, the ”intermediate” ones with $1.23 < \alpha < 1.54$, and the ”fast” decaying light curves with $1.54 < \alpha < 3.41$. With such a selection, each subsample has the same size.

Inspection of Figure 6, presenting the considered long GRBs +XRFs $\alpha$-subsamples distributed along the LT correlation line, clearly reveals separation among these distributions. This behavior is also visible in the normalized cumulative distribution functions plotted in Figure 7. In particular, in Figure 7, the considered samples (all GRBs, long GRBs and long GRBs+XRFs) are presented with respect to the ratio of the GRB afterglow luminosity $L_a^*(T_a^*)$ to the respective luminosity $L_{LT}^*(T_a^*)$ at the fitted correlation line: in the logarithmic scale $\log(L_a/L_{LT}) = \log(L_a) - \log(L_{LT})$. A significant trend between the relative luminosity, $\log(L_a/L_{LT})$, and $\alpha$ is visible in Figure 8, leading, e.g., to negligible KS probability, $P = 1.4 \times 10^{-19}$, that the low and high $\alpha$ subsamples are randomly drawn from a single GRB population.

In Figure 9, we present the distribution of $\log(L_a/L_{LT})$ versus the $\alpha$ index for the long GRBs+XRFs subsample. A linear fit for this distribution is

$$\log L_a - \log L_{LT} = (0.49 \pm 0.17)\alpha - (0.70 \pm 0.25), \quad (1)$$

with Spearman correlation coefficient $\rho = 0.36$, and the probability for random occurrence $P = 10^{-10}$. Using the long GRB subsample only, the correlation has a slightly smaller slope ($0.42$) with $\rho = 0.36$ and $P = 7.7 \times 10^{-10}$. This correlation shows the observed tendency—with respect to the LT correlation line—for higher afterglow luminosity to have steeper light-curve decay.

To better evaluate the errors of the parameters fitted for the analyzed GRB sample, we decided to perform an additional statistical analysis using the Monte Carlo modeling of the data with $3 \cdot 10^4$ simulations in each case. For each GRB, we consider parameters $L_a$, $T_a^*$, and $\alpha$ to have Gaussian distributions around the fitted values, with the distribution width given by the respective 1$\sigma$ uncertainty. Then, we randomly selected from the considered GRB sample—using a bootstrap procedure—the samples to be analyzed, where each GRB parameter was drawn from the respective Gaussian distribution. For each randomly created data sample, we derived the correlation coefficient and the correlation slope by fitting the respective correlation $\log(L_a/L_{LT})$ versus $\alpha$. As presented in the upper panels of Figure 10, the simulations fully confirm the reality of the derived correlation. We find that within the measurement errors the existing correlation coefficient should be approximately between $0.2 < \rho < 0.5$ (mean value 0.35) and the fitted $\log(L_a/L_{LT})$ versus $\alpha$ correlation should have an inclination of $0.3 < a < 0.5$ (mean value 0.41), in agreement with the fitted errors in Equation (1).

Using similar simulations as above, the possibility of randomly obtaining the studied $\log(L_a/L_{LT})$ versus $\alpha$ correlation can also be independently be checked if no systematic relation of $\alpha$ in respect to $L_a$ and $T_a^*$ exists. We performed such an analysis by randomly drawing samples using the procedure

![Figure 6](image6.png)  
*Figure 6.* Distribution of the long GRBs+XRFs subsample on the $(\log L_a, \log T_a^*)$ plane for the three selected $\alpha$ subsamples: $0.53 < \alpha < 1.23$ (red), $1.23 < \alpha < 1.54$ (green) and $1.54 < \alpha < 3.41$ (blue). The black line represents the LT correlation line fitted for all presented GRBs.

![Figure 7](image7.png)  
*Figure 7.* Normalized cumulative distributions function CDF vs. $\log(L_a/L_{LT})$ for the analyzed GRB subsamples in three considered $\alpha$ ranges: $0.53 < \alpha < 1.23$ (red), $1.23 < \alpha < 1.54$ (green), and $1.54 < \alpha < 3.41$ (blue).
Above, again within the bootstrap scheme, but with separately drawing pairs of parameters $L_a$ and $T_T^*$ from the GRB sample, and the $\alpha$ values from the sample of these values for the considered GRBs. Such a procedure removes any correlation between $\alpha$ and other GRB parameters in the sample and shows that the possibility of randomly obtaining the correlation coefficient found in the real data is negligible (Figure 10, lower panels).

4. FINAL DISCUSSION AND CONCLUSIONS

Analysis of the fitted afterglow power-law temporal decay indices for the subsample of long GRBs+XRFs reveals a weak trend toward a steeper decay phase for higher afterglow luminosity $L_a$. The trend turns into a significant correlation if we consider GRB afterglow luminosity scaled to the one expected from the fitted LT correlation, for a given GRB afterglow plateau end time $T_T^*$. As different $T_T^*$ values result from varying properties of the GRB sources, the present analysis can be used to get new insight into the physical nature of such sources.

4.1. Theoretical Models

It is worth noting the attempts in the literature to provide a physical interpretation of the log $L_a$ versus $\alpha$ relation. We can refer to such a model presented by Hascoët et al. (2014; see also Genet et al. 2007) in order to relate the considered $\alpha$ parameter to the microphysics of the reverse shock emission. In the model of Hascoët et al., the energy deposition rate, $E_T$, in the GRB afterglow, varied in time “$r$” with a power-law dependence on the Lorentz gamma factor, $\Gamma(t)$:

$$E_T(\Gamma(t)) = \begin{cases} \dot{E}_* \left( \frac{\Gamma(t)}{\Gamma_*} \right)^{-q} & \text{for } \Gamma(t) > \Gamma_* \\ \dot{E}_* \left( \frac{\Gamma(t)}{\Gamma_*} \right)^{q'} & \text{for } \Gamma(t) < \Gamma_* \end{cases},$$

where the energy scale $\dot{E}_*$ is determined by the total energy injected in the afterglow phase; $q$ and $q'$ are the power-law indices for the time dependence of the energy injection rate. In this model, the $q$ parameter constraints the shape of the plateau phase, while $q'$ carries information about the light-curve temporal decay index after the plateau. The characteristic value of $\Gamma_*$ sets the duration of the plateau. With the assumed power-law radial distribution of the medium surrounding the GRB progenitor, the Lorentz factor evolves as

$$\Gamma(t) = \Gamma_* \left( \frac{t}{T_a} \right)^{-\gamma},$$

where, e.g., $\gamma = 3/8$ for a uniform medium and $\gamma = 1/4$ for a stellar wind. Hascoët et al. derived the light-curve temporal decay indices before $(\alpha_1)$ and after $(\alpha_2)$ the break at the end of the plateau phase as

$$\begin{aligned} \alpha_1 &= \gamma q - 1 \\ \alpha_2 &= -\gamma q' - 1 \end{aligned},$$

so that the flat plateau phase should be present for $q \approx 1/\gamma$, i.e., close to $q = 8/3$ in the uniform medium and $q = 4$ in the wind case. In the presented example, Hascoët et al. (2014) considered the temporal decay index after the plateau.
\[ \alpha_2 = -1.5, \text{ leading to } q' = 1/(2\gamma) \] and the parameters of the central engine energy deposition in the late afterglow stage \[ q' = 4/3 \text{ and } 2, \] for the uniform medium and the wind case, respectively. It should be noted that this example uses the \[ \alpha_2 \] value very close to the mean value of our distribution, \[ \alpha_{\text{mean}} = 1.4 \pm 0.3, \] as visible in the upper panel of Figure 2.

We should remark here that the observed large scatter in the \( \alpha \) distribution seems to be difficult to be explained only by variations of the source radial density profile, influencing the shock propagation. Therefore, we consider the present discussion only as an example of the study based on the \( \alpha \) parameter measurements.

### 4.2. GRB Standardization

As the second aspect of the present study, we consider a possible usage of the measured afterglow light curve \( \alpha \) for physically differentiating the observed GRBs. For example, the revealed \( \log(L_\alpha/L_{\alpha,T}) \) versus \( \alpha \) correlation can be used to search for the procedure, which could enable the standardization of GRBs and eventually reveal a new cosmological standard candle. As an illustrative toy model, for such an approach, we introduce a procedure for GRBs resembling the one used for the standardization of SN Ia light curves by using the so-called Phillips relation between the peak magnitude and the “stretching parameter” (Phillips 1993). In an attempt to scale GRBs with different temporal decay indices \( \alpha \) to the standard source properties, we define the standard GRB as the one characterized by the value of the temporal decay index \( \alpha_0 = 1.4 \), approximately the mean value of the distribution presented in Figure 2. Furthermore, we postulate that the expected “standardized” GRB luminosity, \( L_{\alpha,0} \), can be derived using its measured decay index \( \alpha \) and by scaling it to \( \alpha_0 \) using Equation (1):

\[
\log L_{\alpha,0} = \log L_\alpha + 0.49 (\alpha_0 - \alpha). \tag{5}
\]

This procedure applied for all the events in the analyzed subsample of long GRBs+XRFs results in only a slight increase in the LT correlation coefficient absolute value, from \( r = -0.72 \) for the original (\( \log L_\alpha, \log T_\alpha^{\ast} \)) data to \( r_0 = -0.76 \) for the modified distribution (\( \log L_{\alpha,0}, \log T_\alpha^{\ast} \)). When using the long GRB subsample only the increase in the correlation coefficient is even smaller. This increase in the correlation coefficient is obtained by the fits for quite different shapes of the afterglow light curves and thus different quality of available GRB parameters \( L_\alpha, T_\alpha^{\ast}, \) and \( \alpha \). More detailed analysis of this standardization procedure, with careful consideration of the afterglow light curves for the selected events, is in progress now.

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