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Extending the plateau luminosity-duration anticorrelation

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Abstract. X-ray light curves of *Swift* Gamma-ray Bursts (GRBs) often show a plateau phase between the initial steep decay and the standard afterglow decay. The plateau luminosity and the rest frame plateau end time are known to be anticorrelated. Our aim is to test whether GRBs that show no evidence of plateau can be considered as "very short plateau" cases matching the above correlation. We analyze a sample of 50 GRBs observed by Swift with known redshifts (z), estimating the end time of the plateau and the 0.3−10 keV luminosity at that time. We then consider the GRBs with known z and no evidence of plateau. We confirm the existence of the correlation and provide a unified picture showing that also those X-ray light curves with no evidence of plateau are consistent with it assuming that the start epoch of the long duration afterglow decay is a plateau duration upper limit. We suggest that this result may represent a clue for a unified interpretation of the anticorrelation in the framework of multicomponent models of X-ray emission from GRBs.

1. Introduction

In about 70% of *Swift* detected X-ray light curves of Gamma-ray Bursts (GRBs) a plateau phase has been detected. The physical origin of this plateau feature is still debated. Some authors (e.g. Willingale et al. (2007); Ghisellini et al. (2009)) showed that the typical *Swift* GRB X-ray light curve may be reproduced as the superposition of two emission components, one of them being the standard X-ray afterglow produced by an expanding external shock. An interesting property of the X-ray light curves with plateau phase, is that the brighter is the plateau, the shorter is its duration, providing a statistically significant anticorelation between the plateau luminosity and the rest frame plateau duration (Dainotti et al. 2010, 2011). In addition, longer plateau tend to be softer than shorter ones. The post-plateau decay behavior on average follows the predictions of the fireball model. In a fraction of GRBs, no plateau is observed and the X-ray light curve decays following a simple power law, or a power-law with a single steepening episode with a decay rate consistent with the typical post-plateau one. In this paper we aimed at testing whether those *Swift* GRBs with no evidence of X-ray plateau since first tens-hundreds of seconds from the trigger can be considered as "very short plateau" cases matching the plateau luminosity-duration correlation. This may help in the search for a unified picture to explain all light curve phenomenology.

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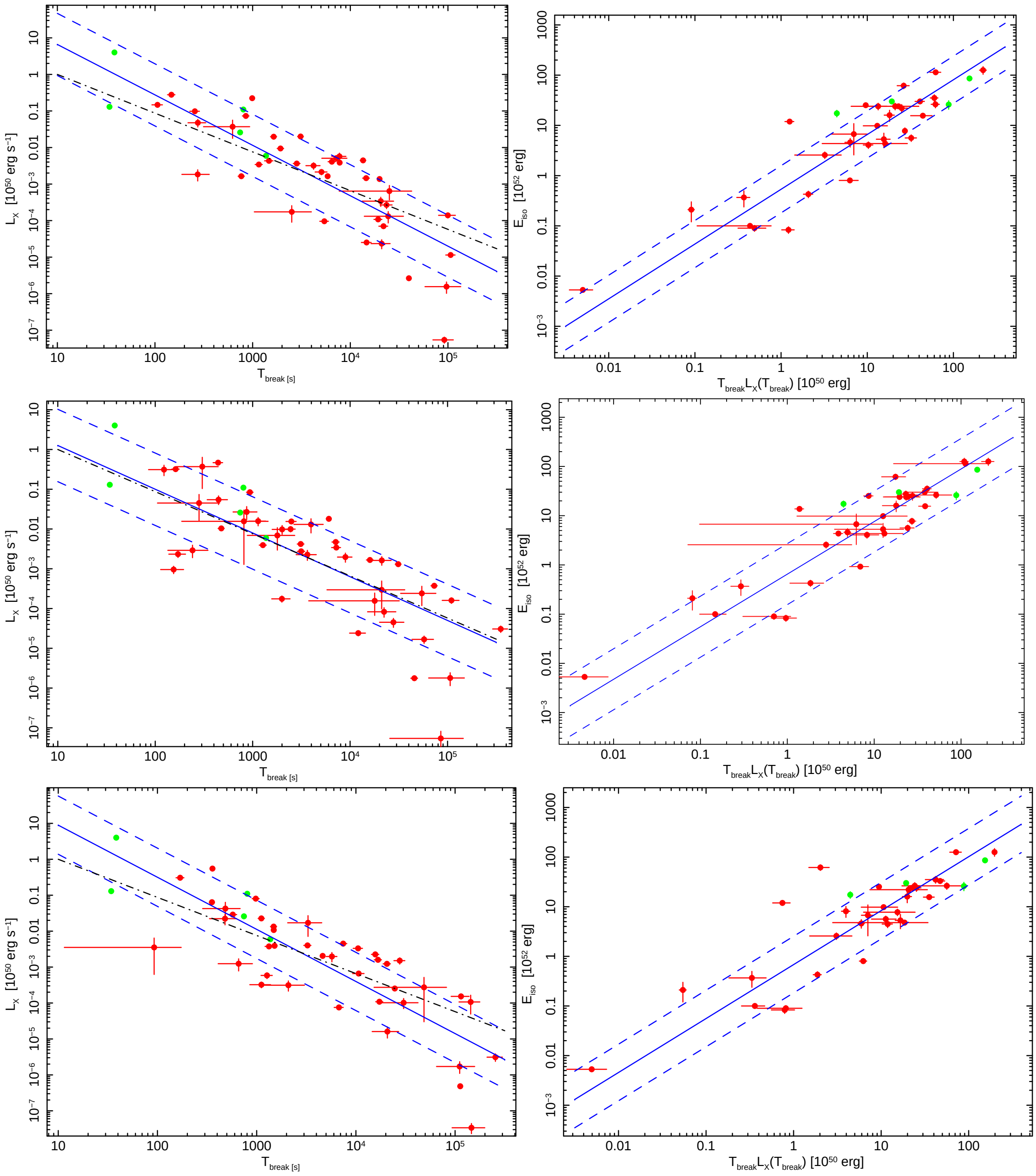

Fig. 1. On the left side, from top to bottom we show the plots of the break time T_{break} versus 0.3−10 keV luminosity at break $L_X(T_{break})$ (labelled as *(a)* in the text) obtained fitting the continuum component of the GRB luminosity light curve with models *(i)*, *(ii)* and *(iii)* described in the text. On the right side, we show the plots of the isotropic energy E_{iso} versus $T_{break}L_X(T_{break})$ (lebelled as *(b)* in the text) in the corresponding three cases. Green points represent the GRBs with single power-law light curve and no breaks (not used for the linear correlation fit). The blue lines represent the best fit solution (solid line) and the 1-σ confidence region (dashed lines) for the linear correlation with intrinsic scatter obtained with bayesian methods in each case. Black dashed dot lines in the left side plots are the Dainotti et al. (2011) solution.

2. Data Analysis and Results

We selected a sample of 158 *Swift* GRBs with measured redshift from the *Swift* launch to September 2010 and downloaded the 0.3−10 keV XRT light curves form the Swift Burst Analyzer Archive created and mantained online at the University of Leicester (Evans et al. 2010). We converted them into luminosity in the 0.3−10 keV energy band with the formula

$$L = 4\pi d_L^2 F/(1+z)^{(2-\Gamma)}$$

where d_L is the luminosity distance of the source from us, z is the redshift, F is the unabsorbed flux in the 0.3−10 keV band and Γ is the photon index of the spectrum, estimated by Evans et al. (2010) as a function of time from the hardness ratio curve. This formula correctly accounts for the k-correction under the assumption that the spectrum is power-law like. This assumption may not be valid in the very early stages of XRT light curves when *Swift* executed quick automatic slews. We carefully checked GRBs showing early (and evolving) broad band spectral curvature to verify that curvature evidences ended before the beginning of the plateau phase. Observed time t was converted to rest-frame time T with the formula $T = t/(1+z)$. The luminosity light curves versus rest frame time where fitted with different analytical models to estimate break times and temporal slopes of different evolutionary phases: *(i)* a broken power-law model with sharp breaks, *(ii)* a broken power-law model with smoothed breaks (e.g. $L_X(T) = N/(T_{break}^{-\alpha_1} + T_{break}^{-\alpha_2})$ in the case of single break at time T_{break}) , *(iii)* the Willingale et al. (2007) model. The fitting procedure included a σ-clipping algorithm to iteratively remove points which deviated more than 3-σ from the best fit curve, and minimize the effect of small scale variability often seen in *Swift* XRT light curves. When X-ray flares were present, the model of the continnum underlying flares was initially estimated adding an appropriate number of analytical flare components and then checked by re-doing the fit without flare components but removing the time intervals in which the flares occurred. We always looked for solutions with all model parameters of the continuum consistent within errors in these two cases. After light curve fitting, we calculated values of the luminosity at break times and estimated the error on this quantity trough error propagation with the covariance matrix of the fit properly taken into account. When no break was detected in the light curve, we calculated the luminosity at the beginning of the XRT observation and its error. Then, we selected GRBs for which isotropic energy (E_{iso}) values can be found in literature (Amati et al. 2008, 2009; Krimm et al. 2009; Nava et al. 2011) and reduced our sample to a total of 50 GRBs, 45 showing at least one break in the light curve and 5 showing a single power-law continuum with no breaks. For this final set of GRBs we plotted *(a)* the time T_{break} of the break marking the end of the plateau phase (when observed) or of the single break detected in the lightcurve (provided that the post break slope is $\alpha_2 > 1$) or of the XRT observation start (when no break was detected) versus the 0.3−10 keV luminosity at that time $L_X(T_{break})$; *(b)* the isotropic energy E_{iso} versus the quantity $T_{break}L_X(T_{break})$ taken as a rough measure of the energy content of a possible emission component, whose origin and nature has not been firmly established yet, that added to standard afterglow emission may produce the plateau phase (Willingale et al. 2007; Ghisellini et al. 2009; Dall'Osso et al. 2011). Plots *(a)* and *(b)* were produced separately for the the three light curve models *(i)*, *(ii)* and *(iii)* (see Fig. 1).

The plots in Fig. 1 show the linear anticorrelation between T_{break} and $L_X(T_{break})$ in the log-log plane (known as the plateau luminosity-duration anticorrelation of Dainotti et al. (2010, 2011)) and the linear correlation between E_{iso} and $T_{break}L_X(T_{break})$ in the log-log plane already observed by Ghisellini et al. (2009). We calculated the Spearman correlation coefficient ρ along with slope m and intrinsic scatter s of all these linear correlations with bayesian fits to the following models: $\log(L_X(T_{break})) = m_a \log(T_{break}) + q_a$ with intrisic scatter s_a in case *(a)* and $\log(E_{iso}) = m_b \log(T_{break}L_X(T_{break})) + q_b$ with intrisic scatter s_a in case *(b)*. The fits were always performed excluding the 5 GRBs with single power-law light curve and no breaks (green

Table 1. Estimates of Spearman correlation coefficient ρ, slope (m), intercept (q), intrinsic scatter (s) and probability of chance correlation (P) of the observed linear correlations obtained with bayesian fit methods. The a suffix refers to the $\log(T_{break})$ versus $\log(L_X(T_{break}))$ anticorrelation, and the b suffix to the $\log(E_{iso})$ versus $\log(T_{break}L_X(T_{break}))$ correlation. Reported errors are at the 90% confidence level.

	power-law sharp breaks model *(i)*	power-law smooth breaks model *(ii)*	Willingale model *(iii)*
ρ_a	-0.81	-0.78	-0.81
m_a	-1.38±0.16	-1.10±0.18	-1.45±0.19
q_a	52.2±0.6	51.2±0.7	52.4±0.7
s_a	0.85±0.10	0.90±0.10	0.81±0.10
P_a	2.4×10^{-10}	3.0×10^{-10}	1.7×10^{-10}
ρ_b	0.85	0.87	0.79
m_b	1.8×10^{-9}	2.4×10^{-11}	7.9×10^{-8}
q_b	0.98±0.11	1.04±0.11	1.04±0.11
s_b	2.63±5.7	-0.36±5.5	2.65±5.7
P_b	0.47±0.10	0.57±0.10	0.62±0.10

points in the plots). Results are shown in Table 1. We find that the parameters of the correlations are roughly independent of the model used to fit the light curve continuum. Possible differences should be further investigated with a larger sample of bursts. Our results are consistent within errors with the Dainotti et al. (2011) and Ghisellini et al. (2009) results, respectively. The 5 GRBs that do not show breaks in their light curves are consistent with the correlations when we use the XRT observation start for T_{break} and the initial luminosity of the lightcurve for $L_X(T_{break})$.

3. Conclusions

We tested the known plateau luminosity-duration anticorrelation for *Swift* GRBs and confirmed it as a light curve model independent feature. We also reproduced the known correlation between the burst isotropic energy and the energy budget of the (possible) emission component contributing to the plateau, and showed that GRBs with no break in the light curves can match both correlations when the start time and initial luminosity of the XRT observation are used. These GRBs can then be regarded as GRBs with a very short plateau phase (virtually ended before the start of the observation) or particularly high energy budget in the plateau component. The two correlations we investigated in the present work can both accounted for in the framework of an energy injection model from a spinning down magnetar at the center of the fireball (Dall'Osso et al. 2011; Xu & Huang 2011). A very promising systematic modeling of *Swift* GRBs luminosity light curves with the Dall'Osso et al. (2011) model is on going, to check whether the observed match of single power-law light curves with the empirical correlations can also be explained.

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