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A tight correlation for GRB afterglows with canonicalİ light curves

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Gamma -ray bursts (GRBs) observed up to redshifts $z > 8$ are fascinating objects to study due to their still unexplained relativistic outburst mechanisms and a possible use to test cosmological models. Our analysis of 77 GRB afterglows with known redshifts revealed a physical subsample of long GRBs with canonical plateau breaking to power-law light curves with a significant *luminosity* L_X^* *-break time* T_a^* correlation in the GRB rest frame. It proves that within the full sample of afterglows there exist physical subclasses revealed here by tight correlations of their afterglow properties. Following this analysis we extend it to correlations between the afterglow and the prompt emission GRB physical parameters. We reveal a tight physical scaling between the mentioned afterglow luminosity L_a^* and the prompt emission *mean* luminosity $< L_p^* >_{45} \equiv E_{iso}/T_{45}^*$, with the Spearman correlation coefficient reaching 0.95 for the data subsample with most regular light curves. We also analyzed correlations of L_a^* with several other prompt emission parameters, including the isotropic energy E_{iso}.

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1. Introduction

The detection of GRBs up to high redshifts (z=8.2; [36, 42]), larger than Type I Supernovae Ia (SNeIa) ($z_{max} = 1.77$; [35]), makes these objects appealing for possible use in cosmology. The problem is that GRBs seem not to be standard candles, with their energetics spanning over 7 orders of magnitude. Anyway, several GRB luminosity indicators [1, 18, 31, 22, 28, 29, 21, 33] and their use to constrain cosmological parameters [19, 30, 41, 26] have been proposed till now. Furthermore, [10] following [9] have derived an updated GRB Hubble diagram using the $\log L_X^*$–$\log T_a^*$ ("LT") [1] correlation with five other two-dimensional GRB correlations used by [39]. However, the problem of large data scatters in the considered luminosity relations [5, 44] and a possible impact of detector thresholds on cosmological standard candles [38] have been discussed controversially [8]. Among these attempts, [12] have proposed a way to standardize GRBs as distance indicator with the discovery of the LT anti-correlation. The fitted power-law relation is $\log L_X^* = \log a + b \cdot \log T_a^*$; the constants a and b are determined using the [16] method. One may note that an analogous LT relation was derived phenomenologically by [23] and [25] and that the LT correlation is also a useful test for the models of [7] and [15].

We study the LT correlation using the extended GRB data set and demonstrate the existence of a physical LT scaling for "canonical" light curves in the GRB rest frame. Revealing these physical correlations can help the (still unclear) interpretation of the physical mechanisms responsible for the GRB X -ray afterglow emission and can infer important information about the nature of the emitting source. We also find that the prompt-afterglow correlations are more significant if one uses the prompt emission mean luminosity instead of the energy E_{iso}. This work reveals an important fact: any search for physical relations between GRB properties should involve selection of well constrained physical GRB subsamples. Usage of all available data introduces into analysis the events with highly scattered intrinsic physical properties, what smooths out possible correlations, and may lead to systematic shifts of the fitted relations, e.g. [13]. It is likely that a substantial fraction of the observed large scatter is introduced because we are observing different classes of GRBs with different progenitors and/or in different physical conditions. Identifying such subclasses may be the real challenge. Separating short and long GRBs is too simplistic. Below, we demonstrate that a particular class of canonical GRBs exists within the full sample of long GRBs. In the paper we use CGS units: [erg] for energy, [erg/s] for luminosity and [s] for time. All quantities used for correlation analysis are computed in the GRB rest frames (we indicate such quantities using a superscript *, E_{iso} is in GRB rest frame from its definition).

2. Data selection and analysis

We have analyzed a sample of all afterglows with known redshifts detected by Swift from 2005 January up to 2009 April, for which the light curves include early X-ray Telescope (XRT) data and therefore can be fitted by a Willingale's phenomenological model [43]. The redshifts z are taken from the Greiner's Web site http://www.mpe.mpg.de/∼jcg/grb.html in agreement with

[1] We use the index "$*$" to indicate quantities measured in the GRB rest frame in which $L_X^* \equiv L_X^*(T_a^*)$ is an isotropic X-ray luminosity in the time T_a^*, the transition time separating the afterglow plateau and the power-law decay phases [12].

the values reported by [4, 6]. Our data analysis, including derivation of T_a^* and L_X^* (in units of (s) and ($ergs^{-1}$), respectively) for each afterglow, follows [12] and [43]. The source rest -frame luminosity in the Swift XRT bandpass, $(E_{min}, E_{max}) = (0.3, 10)$ keV, is given taking account of the K-correction for cosmic expansion [3] by the following expression:

$$L_X^* = \frac{4\pi D_L^2(z) F_X}{(1+z)^{1-\beta_a}} \tag{2.1}$$

where $F_X = F_a \exp(-\frac{T_p}{T_a})$ is the observed flux (erg/cm^2/s)at the time T_a, $D_L(z)$ is the GRB luminosity distance for the redshift z, computed assuming a flat ΛCDM cosmological model with $\Omega_M = 0.291$ and $h = 0.697$. We have derived a spectral index β_a for each GRB afterglow using the Evan's Web site http://www.swift.ac.uk/xrt curves [17] setting a filter time as $T_a \pm \sigma_{T_a}$; the T_a values together with their errorbars, σ_{T_a}, are derived in the fitting procedure used by [43].

A choice of the Willingale model to obtain the fitted parameters F_a,T_a and T_p as a representation for the X-ray GRB light curves allows us to use a homogeneous sample of events to study physical correlation in a statistical way. To analyze how the accuracy of fitting the canonical light curve to the data influences the studied correlations, we use the respective logarithmic errors bars, $\sigma_{L_X^*}$ and $\sigma_{T_a^*}$, to formally define a fit -error parameter $u \equiv \sqrt{\sigma_{L_X^*}^2 + \sigma_{T_a^*}^2}$. This definition is used to distinguish the canonical shaped light curves from the more irregular ones, perturbed by "secondary" flares and various non-uniformities. (For the discussion of systematics issues regarding the choise of systematics see [14], while for general discussion on systematics for luminosity relations see [11]). The symmetric error bars quoted are computed with the method of [16] that takes into account the hidden errors and thus gives greater error estimates than the ones obtained with the Marquardt Levemberg algorithm [24].

Our analyzed sample of 77 GRBs from the redshift range $0.08 - 8.26$ includes afterglows of 66 long GRBs and 11 GRBs whose nature is debated, the IC between long and short GRBs described by [32] as an apparent (sub)class of bursts with a short initial pulse followed by an extended low-intensity emission phase. Our long GRB sample also includes eight X -ray flashes (XRFs; 060108, 051016B, 050315, 050319 [20], 050401, 050416A, 060512, 080330 [37]). XRFs are scattered within the long GRB distribution in Figure 1, providing further support to a hypothesis that both these phenomena have the same progenitors [27]. To study physically homogeneous samples, we decided here to analyze the sub-samples of 66 long GRBs (including XRFs).

Regarding the investigation of the correlations of L_a^* with several other prompt emission parameters we can estimate the characteristic luminosity of a burst using different characteristic times, T_{45}, T_{90} and T_p, where T_{45} is the time spanned by the brightest 45 per cent of the total counts above the background [34] and T_p is the fitted transition time in which the exponential decay in the prompt phase changes to a power law decay. Here we define $< L_p^* >_{45} \equiv E_{iso}/T_{45}^*$, $< L_p^* >_{90} \equiv E_{iso}/T_{90}^*$ and $< L_p^* >_{Tp} \equiv E_{iso}/T_p^*$ and we have analyzed correlations between logarithms of the prompt emission parameters E_{iso}, $< L_p^* >_{45}$, $< L_p^* >_{90}$, $< L_p^* >_{Tp}$, and the parameters L_a^* characterizing the afterglow light curve. The E_{iso}, T_{90} and T_{45} values are listed in [4, 6], while T_p is the one used to fit the Willingale model.

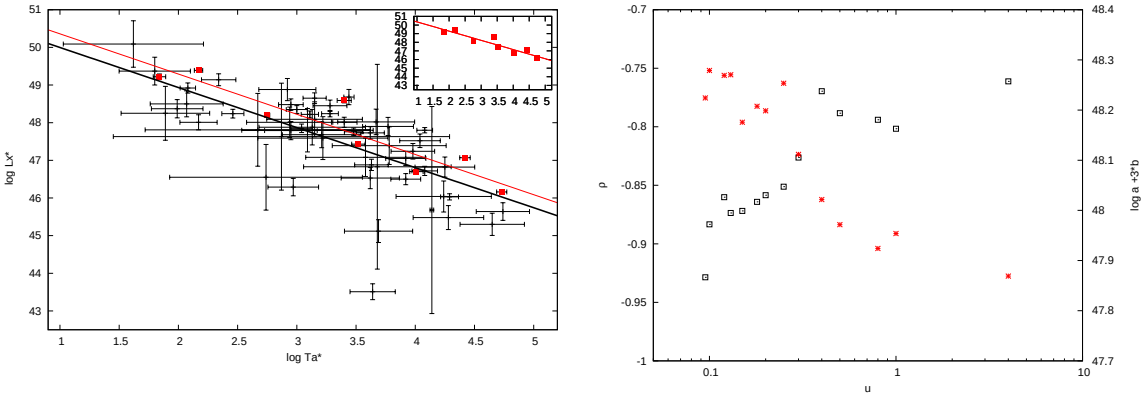

Figure 1: Left panel: L_X^* vs T_a^* distribution for the sample of 62 long afterglows with $u < 4$, with the fitted correlation line in black. The upper red line, fitted to the 8 lowest error (red) points, forms approximately an upper envelope of the full distribution. The upper envelope points with the fitted line are separately presented in an inset panel. On the right panel, Left vertical axis: correlation coefficients $\rho(\log L_X^*, \log T_a^*)$ vs the error parameter u for the long GRBs are presented with black squares. The right vertical axis: normalizations of the fitted correlation lines at $\log T_a^* = 3.0$ vs u are presented with red asterisks.

3. The results

The obtained "L_X^* versus T_a^*" distributions for long GRBs (Figure 1, [2]) clearly demonstrate the existence of significant LT correlations, characterized by the Spearman correlation coefficient, ρ, a non-parametric measure of statistical dependence between two variables [40]. From a visual inspection of Figure 1 and the analysis discussed later in Figure 1 right panel one can note that the lowest error events concentrate in the upper part of the distribution, forming a highly correlated subsample of the full distribution. To visualize this effect we decided to select eight points with smallest errors to define our limiting upper envelope subsample, $u < 0.095$, see the inset panel in Figure 1.

For the full sample of 66 long GRBs one obtains $\rho_{LT} \equiv \rho(\log L_X^*, \log T_a^*) = -0.68$ and a probability of occurring of such correlation by chance within the uncorrelated sample $P = 7.60 \times 10^{-9}$ (cf. [2]). If we remove a few large error points by imposing a constraint $u < 4$, we have a limited sample of 62 long GRBs presented in Figure1, with $\rho_{LT} = -0.76$, $P = 1.85 \times 10^{-11}$, and the fitted correlation line parameters $\log a = 51.06 \pm 1.02$ and $b = -1.06^{+0.27}_{-0.28}$, while for the *upper envelope* sample we obtain, respectively, $\rho_{LT} = -0.93$, $P = 1.7 \times 10^{-2}$, $\log a = 51.39 \pm 0.90$ and $b = -1.05^{+0.19}_{-0.20}$.

To study the fit error systematic of GRB afterglows we show below, in Fig 1 on right panel, how the limiting upper value for u in the analyzed sample, i.e. how selecting the afterglows with increasing precision of L_X^* and T_a^* fits, influences the LT correlation. We present changes of the ρ_{LT} converging -with decreasing u -toward a nearly linear LT relation, as observed for our upper envelope sample. In the figure, e.g., we have 62 long GRBs for $u = 4$, 33 GRBs for $u = 0.3$, 19 GRBs for $u = 0.15$, 13 GRBs for $u = 0.12$ and eight GRBs left for our limiting $u = 0.095$. A presented accompanying systematic shift upward of the fitted correlation - as measured in the middle of the

[2] See the data table for all long and IC GRBs at http://www.oa.uj.edu.pl/M.Dainotti/GRB2010

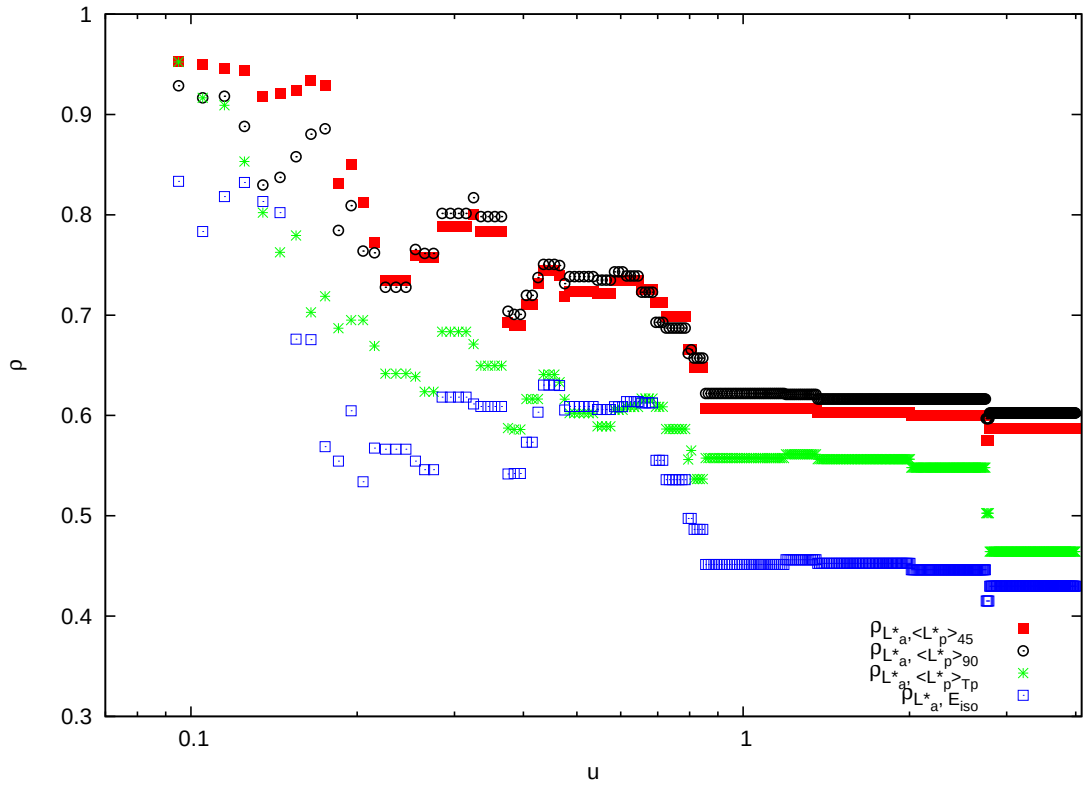

Figure 2: Correlation coefficients ρ for the distributions $\log L_a^* - \log < L_p^* >_{45}$ (red squares), $\log L_a^* - \log < L_p^* >_{90}$ (black circles), $\log L_a^* - \log < L_p^* >_{Tp}$ (green asterixes) and $\log L_a^* - \log E_{iso}$ (blue squares) for the long GRB subsamples with the varying maximum error parameter u.

distribution as $\log a - 3.0 \cdot b$ (the fitted correlation line at selected $\log T_a^* = 3.0$) -with decreasing u, proves that the limiting $u \ll 1$ subsample forms the brightest afterglows in the LT distribution. This regular trend allows us to conclude that the subclass of all long GRBs with “canonical" afterglows forms a well defined physical class of sources exhibiting high correlation of their afterglow parameters. Presence of GRBs with light curves deviating from the [43] model increases the scatter in the LT distribution, with larger error points distributed preferentially below the small error ones. Let us also note that our limiting upper envelope subsample includes GRBs with redshifts reaching the maximum value of ‘only’ 2.75, while the most distant GRB with $z = 8.26$ disappears from the analyzed sample after decreasing u below 0.25.

We have represented changes of the ρ_{LT} converging -with decreasing u for the $\log L_a^*$–$\log < L_p^* >_{45}$ and the other distributions considered in this study, involving E_{iso}, $< L_p^* >_{90}$ and $< L_p^* >_{Tp}$. The highest correlated sample is represented by the $\log L_a^*$–$\log < L_p^* >_{45}$, but also the other distributions show significant correlations, with the lowest u events forming in all cases tightly correlated subsamples of the full distribution (Fig. 2).

4. Summary

In this analysis we present the updtodate of the $L_a^* - T_a^*$ (LT) correlation and new signifi-

cant correlations between the luminosity of the afterglow plateau phase, L_a^*, and parameters of the prompt emission, including the mean luminosities and the integral energy derived for this emission. For the light curves which are smooth and well fitted by the [43] phenomenological model we find tight correlations in the analyzed distributions, showing that only GRBs with regular light curves exhibit strict physical scalings between their observed characteristics. Thus only such events can be considered to form the standard GRB sample, to be used for both GRB detailed physical model discussion and, possibly, to work out the GRB-related cosmological standard candle. A progress in both issues requires to increase an observed number of the canonical light curve GRBs, not by simply increasing the total number of GRBs with know redshifts. GRBs with the light curve non-uniformities exhibit weaker correlations of the plateau phase and the prompt emission energetics.

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