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On the intrinsic nature of the updated luminosity time correlation in the X-ray afterglows of GRBs

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Abstract. Gamma-ray bursts (GRBs) observed up to redshifts $z > 9.3$ are fascinating objects to study due to their still unexplained relativistic outburst mechanisms and a possible use to test cosmological models. Our analysis of all GRB afterglows with known redshifts and definite plateau (100 GRBs) reveals not only that the luminosity $L^*_X(T_a)$ - break time T^*_a correlation, called hereafter LT, (Dainotti *et al.* 2010a) is confirmed with higher value of the Spearman correlation coefficient for the new updated sample, but also reveals its intrinsic nature throughout the analysis of the Efron & Petrosian (1992) test. The above mentioned test is performed to check if there is redshift evolution in both the luminosity and time. This test shows that the correlation still holds probing that its nature is intrinsic and it is not due to selection biases. The novelty of this approach is that the Efron & Petrosian method has been applied for the first time for a two parameter correlation that involves not only luminosities, but also time. Notwithstanding the intrinsic nature of the correlation, the correction of the observables for the effect of redshift evolution does not lead to a significantly tighter correlation and thus to a better redshift estimator. Therefore, the usage of the L^*_a correlation is limited, at least with the present data analysis, to constrain physical models of plateau emission. With an enlarged data sample in the future the aim will be to make the luminosity time correlation a useful redshift estimator.

Keywords. cosmological parameters - gamma-rays bursts: general, -radiation mechanisms: nonthermal

1. Introduction

GRBs are the farthest, up to z = 9.46, and the most powerful, up to 10^{54} ergs/s, objects ever observed in the Universe. Finding out universal properties which could be revealed by looking for strict relations among their observables plays a crucial role in understanding processes responsible for GRBs. But, GRBs seem to be everything but standard candles, with their energetics spanning over 8 orders of magnitude. Notwithstanding the variety of their different peculiarities, some common features have been identified thanks to the observation of GRBs by the *Swift* satellite which provides a rapid follow-up of the afterglows in several wavelengths with better coverage than previous missions. *Swift* revealed a more complex behavior of the lightcurves than the broken power-law assumed in the past (O' Brien *et al.* 2006). In the lightcurves observed by Swift one can identify two, three and even more segments in the afterglows. The second segment, when it is flat, is called plateau emission. A significant step forward in determining common features in the afterglow lightcurves has been made by the analysis of the X-ray afterglow lightcurves of the full sample of *Swift* GRBs showing that they may be fitted by the same analytical expression (Willingale *et al.* 2007). This provides the unprecedented opportunity to look for universal features that would allow us to recognize if GRBs are standard candles. Therefore, studies of correlations between GRB observables, E_{iso} - E_{peak} (Lloyd & Petrosian 1999, Amati *et al.* 2009), E_{γ} - E_{peak} (Ghirlanda *et al.* 2004, Ghirlanda *et al.* 2006), L - E_{peak} (Schaefer 2003, Yonekotu 2004), L - V (Fenimore & Ramirez - Ruiz 2000, Riechart *et al.* 2001, Norris *et al.* 2000) are the attempts pursued in this direction. However, the problem of large data scatter in the considered luminosity correlations (Butler *et al.* 2009, Yu *et al.* 2009) and a possible impact of detector thresholds on cosmological standard candles (Shahmoradi & Nemiroff 2009, Petrosian 1998, Petrosian *et al.* 1999, Petrosian 2002) are also debated issues (Cabrera *et al.* 2007) and should be taken into account.

Within the framework of correlations a new phenomenological one for long GRBs (Dainotti *et al.* 2010a, Dainotti *et al.* 2011, Dainotti *et al.* 2008) between the luminosity at the end of the plateau phase, L^*_X and its duration, T^*_a has been discovered (We denote with $*$ the rest frame quantities). In particular, the established behaviour is $\log L^*_X = \log a + b \log T^*_a$, where a (the normalization parameter) and b (the slope) are constants obtained by the fitting procedure. The above anticorrelation has already been confirmed in the literature (Ghisellini *et al.* 2008, Yamazaki 2009) and it is also a useful test for theoretical models (Cannizzo & Gehrels 2009, Cannizzo *et al.* 2011, Dall'Osso *et al.* 2011, Bernardini *et al.* 2011). Here, we study the LT correlation in order to test its intrinsic nature and what is its intrinsic slope, because this is the first step to cast light on the nature of the plateau emission and provide further constrains on the theoretical models. We have found the true power law of the LT correlation corrected for possible data truncation due to the instrumental threshold. This step is necessary to assess the possibile usage of the LT correlation as a distance estimator.

2. Data Analysis

We have extented the analysis of the LT correlation using a sample of 100 afterglows of all GRBs, long, short with extended emission and X-ray Flashes with known redshifts (from 0.08 to 9.4) detected by Swift from 2005 January up to 2011 May, for which the light curves include early X-ray Telescope (XRT) data and can be fitted by the Willingale's *et al.* phenomenological model 1. The present data analysis presents a modification compared to previous papers (Dainotti *et al.* 2008, Dainotti *et al.* 2010), in which the Swift BAT+XRT lightcurves of GRBs were fitted assuming that the time rise of the afterglow, t_a started at the same time as the beginning of the decay phase of the prompt emission, T_p, namely $t_a = T_p$. In such a way the fitting of the afterglow was related throughout this parameter to the prompt emission. In the present analysis we aim to have an independent measure of the afterglow parameters, therefore we have left t_a free of vary.

For further details of the computation of the source rest -frame luminosity and the spectral fitting procedure see Dainotti *et al.* (2010), Evans *et al.* (2009).

The best fit for the slope of the new observed $L^*_X(T_a)$-T^*_a correlation with 100 GRBs is -1.6 while in the previous sample with 77 GRBs the slope was roughly -1.1. We investigated several hypotheses to explain the change of the slope in the correlation: a) If the method of the fitting changed the result, it would mean that the correlation is model dependent and it would not be intrinsic; b) the changes are caused by the redshift evolution of both luminosity and time redshift evolution which is different in the two samples due to the difference in the redshift distribution. The two samples have 53 GRBs in common.

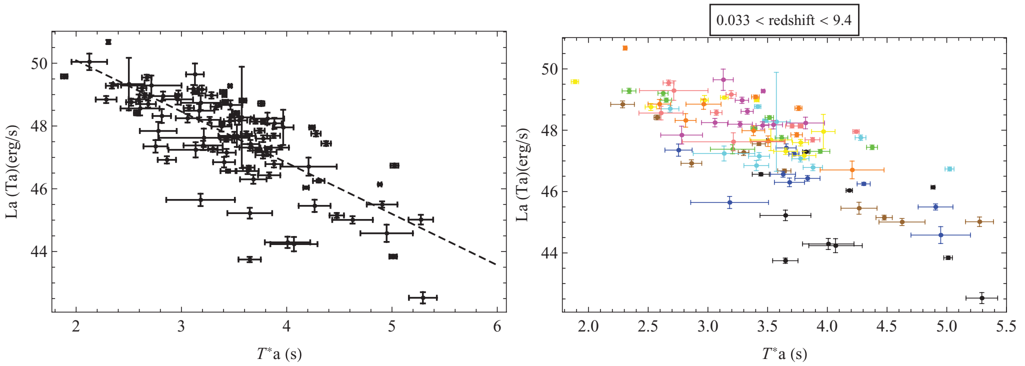

Figure 1. Left panel: L_X^* vs T_a^* distribution for the sample of 100 afterglows of long GRB and short GRB with extended emission, with the fitted correlation line in black. Right panel: L_X^* vs T_a^* distribution divided in 8 redshift bin, black $z \leqslant 0.69$, brown $0.69 < z \leqslant 1.0$, blue $1.0 < z \leqslant 1.49$, cyan $1.49 < z \leqslant 2.15$, yellow $2.15 < z \leqslant 2.67$, green $2.67 < z \leqslant 3.2$, pink $3.2 < z \leqslant 4.1$ and red for $z > 4.1$

3. Methodology and results

To answer the previous questions it is imperative to first determine the true correlations among the variables, not those introduced by the observational selection effects, before obtaining the individual distributions of the variables themselves and the correlations among them. With the term selection effect or bias we refer to the distortion of statistical analysis, resulting from the method of collecting samples, namely gathering data from a certain satellite with a certain flux limit would prevent us from seeing a truly representative sample of events. Therefore, we present here in left panel, see Fig. 1 the observed $L_X^*(T_a)$-T_a^* distribution divided in 8 equipopulated redshift bins. We have checked that the correlation coefficient of every subsample and the slope are still compatible in 1 σ, but for the redshift bin between $3.2 < z < 4.1$ (pink points) for which the correlation coefficient is negligible. So, the test applied in Dainotti *et al.* (2011a) alone is not sufficient to guarantee the lack of evolution in redshift of the LT correlation. Therefore, we have applied the Efron & Petrosian (1992) technique (EP) that corrects for instrumental threshold selection effect and redshift evolution and has been already successfully applied to GRBs (Lloyd & Petrosian 1999). In general, the first step required for this kind of investigation is the determination of whether the variables of the distributions, L_X^* and T_a^*, are correlated with redshift or are statistically independent. For example, the correlation between L_X^* and the redshift, z, is what we call luminosity evolution, and independence of these variables would imply absence of such evolution.

The EP method prescribed how to remove the correlation by defining new and independent variables. Therefore, following the approach used for quasars and blazars (Singal *et al.* 2011a, 2011b), the new variables will not evolve with redshift, namely they will not be affected by redshift evolution, and the correction will be the following $L'_X \equiv L_X^*/g(z)$, where the function $g_z = (1+z)^{k_L}$ describes the luminosity evolution, and $T'_a \equiv T_a^*/f(z)$ where $f(z) = (1+z)^{k_T}$ describes the time evolution. We denote with $'$ the not-evolved quantities. The EP method deals with data subsets that can be constructed to be independent of the truncation limit suffered by the entire sample. This is done by creating ‘associated sets’, which include all objects that could have been observed given a certain limiting luminosity. A specialized version of the Kendall-rank correlation coefficient τ, a statistic tool used to measure the association between two measured quantities, takes into account the associated sets and not the whole sample and produces a single parameter whose value directly rejects or accepts the hypothesis of independence. The values of k_L and k_T for which $\tau_{L,z} = 0$ and $\tau_{T,z} = 0$ are the ones that best fit the luminosity and time evolution, respectively. With these values of k_L and k_T we can determine the not-evolved T'_a and L'_X. In the space of T'_a and L'_X we have applied again the method of the associated sets to derive the best estimate of the intrinsic slope of the correlation. We have tested this procedure using Monte Carlo simulations designed to resemble the observations, but with known distributions of uncorrelated and correlated luminosities, L'_X, and time, T'_a, and subjected to a truncation similar to the actual data. The simulations confirm the results obtained from the EP technique with the observed data. We can conclude that the LT correlation exists indeed with an intrinsic correlation slope ranging from −1.6 to −2.0. There is no relevant redshift evolution both in time and luminosity, so the correlation is preserved. Therefore, the LT correlation can be used to discriminate among theoretical models and to cast light on the nature of the plateau emission.

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Discussion

Amati Lorenzo: Did you perform simulations in order to evaluate selection effects introduced by the cuts of low accurate variables, Lx-Ta?

Dainotti Maria G.: Indeed, we have performed simulations that confirms that the correlation is intrinsic and the more accurate the measurement of the variables the tigher the correlation is implying the existence of a subclass of GRBs with well definite properties.