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Correlations of Gamma-ray Bursts between the plateau and the prompt emission luminosities

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Abstract. To find out the astrophysical processes responsible for Gamma Ray Burst (GRB), it is crucial to discover and understand the relations between their observational properties. This work was performed in the GRB rest frames using a sample of 62 long Swift GRBs with known redshifts. Following the earlier analysis of the afterglow, luminosity L^*_a – break time T^*_a correlation, we extend it to correlations between the afterglow and the prompt emission GRB physical parameters. We find a tight physical scaling between the mentioned afterglow luminosity L^*_a and the prompt emission mean luminosity $< L^*_p >_{45} \equiv E_{iso}/T^*_{45}$. The distribution, with the Spearman correlation coefficient reaching 0.95 for the data most accurately fitted subsample scales approximately as $L^*_a \propto < L^*_p >_{45}{}^{0.7}$. We have also analyzed correlations of L^*_a with several prompt emission parameters, including the isotropic energy E_{iso} and the peak energy in the νF_ν spectrum, E_{peak}. As a result, we reveal significant correlations also between these quantities discovering that the highest correlated GRB subsample in the afterglow analysis leads also to the highest prompt-afterglow correlations. Such events can be considered to form a sample of standard GRBs for astrophysics and cosmology.

Key words. gamma-ray burst: general, radiation mechanisms : non-thermal

1. Introduction

To better understand processes responsible for GRBs and possibly to create a new GRB-based cosmological standard candle, one should find out universal properties which could be revealed by looking for strict relations among their observables. But, GRBs seem to be everything but standard candles, with their energetics spanning over 8 orders of magnitude. However, the revealed correlations of E_{iso} - E_{peak} Amati et al. (2009), E_γ - E_{peak} Ghirlanda et al. (2004, 2006), L - V Fenimore & Ramirez - Ruiz (2000) and other proposed luminosity indicators allowed for expecting a quick progress in the field. The problem of the scatter in all the correlations is that it is larger than the spread expected from the z dependence alone. Among various attempts, a way to standardize GRBs with the discovery of $\log L^*_a$–$\log T^*_a$ ('LT') anti-correlation have been proposed Dainotti et al. (2008), where $L^*_a \equiv L^*_X(T_a)$ is an isotropic X-ray luminosity in the time T^*_a, the transition time separating the plateau and the power-law decay after-

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Send offprint requests to: M.G. Dainotti glow phases and, henceforth, we use the index '$*$' to indicate quantities measured in the GRB rest frame. We have presented Dainotti et al. (2010) an analysis revealing that the long GRBs with smaller value of the error parameters in the afterglow are much more tightly LT correlated as compared to the full sample of long GRBs. The LT correlation has been already applied to derive cosmological parameters Cardone et al. (2009, 2010). Moreover, one may note that an analogous LT relation was derived phenomenologically Ghisellini et al. (2009); Yamazaki (2009) and it is also a useful test for the models Cannizzo & Gehrels (2009); Cannizzo et al. (2011); Dall'Osso et al. (2010).

Here we study correlations between the *afterglow* luminosity parameter L^*_a and the energetics and mean luminosity of the *prompt emission*. We demonstrate existence of significant correlations among the afterglow plateau and the prompt emission phases, which reach maximum for the *Swift* light curve well fitted by a simple analytical expression proposed by Willingale et al. (2007). The revealed high correlations indicate the expected physical coupling between the GRB prompt and afterglow energetics, which is quite tight for the well fitted afterglow lightcurve GRBs. 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, see Dainotti et al. (2010). 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. In the paper we use the same units and notation as in Dainotti et al. (2011).

2. Data selection and analysis

We can estimate the characteristic luminosity of a burst using different characteristic times, T_{45} (Riechart et al. 2001), T_{90}Kouveliotou et al. (1993) and T_p (Willingale et al. 2007). 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}, $< L^*_p >_{45}$, $< L^*_p >_{90}$, $< L^*_p >_{Tp}$, E_{peak}, V and the parameters L^*_a and T^*_a characterizing the afterglow light curve.

The GRB sample used in the analysis and the derivations of T^*_a and L^*_a for each afterglow follow Dainotti et al. (2011). From a homogeneous sample of long GRBs we extract subsamples of GRBs with improving Willingale's light curve fit quality.

As a measure of the fit accuracy (L^*_a, T^*_a) we use the error parameter u :

$$u \equiv \sqrt{\sigma^2_{L^*_a} + \sigma^2_{T^*_a}} \qquad (1)$$

as defined in Dainotti et al. (2010). One can note that it is also a relative error in measuring the X-ray energy scale $L^*_a \cdot T^*_a$. In this study the limiting long GRB subsamples are: the largest one consisting of 62 long GRBs with $u \leq 4$, hereafter called 'U4', and the previously called the *upper envelope* subsample, consisting of 8 GRBs with smallest afterglow fit errors, $u \leq 0.095$, hereafter called 'U0.095'. We also analyze selected intermediate subsamples with the maximum u values decreasing from 4.0 to 0.095, in attempt to reveal systematic variations of the studied correlations. This choice follows our previous paper, Dainotti et al. (2010), and the discussion of systematics issues has been already presented, Dainotti et al. (2011).

3. Prompt-afterglow correlations

The derived $\log L^*_a$–$\log < L^*_p >_{45}$ distribution is presented for the U4 subsample of 62 long GRBs on Fig. 1a, where, also, the U0.095 subsample of 8 GRBs with the most accurate determination of L^*_a and T_a is indicated.

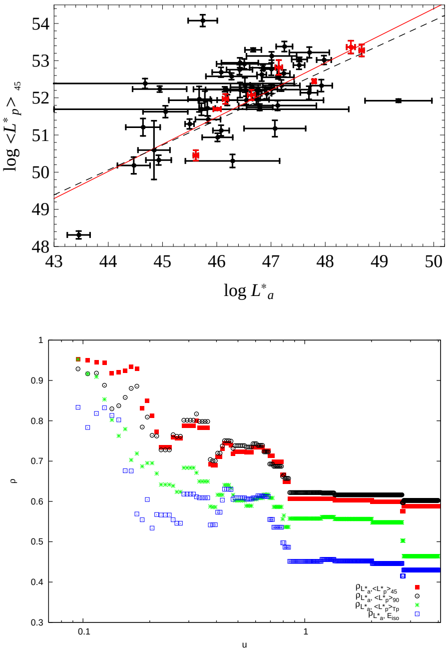

Fig. 1. Figure 1a:L^*_a versus $< L^*_p >_{45}$ distribution for the U4 sample (all points), with the fitted correlation dashed line in black. The red line is fitted to the 8 lowest error (red) points of the U0.095 subsample. Figure 1b: Correlation coefficients ρ for the distributions $\log L^*_a - \log < L^*_p >_{45}$ (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.

The distribution illustrates a significant correlation of the considered luminosities, with the Spearman correlation coefficient, ρ, equal 0.64 for U4, but growing to the value of 0.98 for U0.095 sample (Fig. 1b). The fitted distribution reads $\log L^*_a \propto \log < L^*_p >^a_{45}$, with $a = 0.67^{+0.14}_{-0.15}$ and $a = 0.73^{+0.16}_{-0.11}$ for U4 and U0.095 samples, respectively, agreeing with the fit errors. The other distributions considered in this study, involving E_{iso}, $< L^*_p >_{90}$, $< L^*_p >_{Tp}$ instead of $< L^*_p >_{45}$ also show significant correlations, with the lowest u events forming - in all cases- tightly correlated subsamples of the full distribution (Fig. 1b). The resulting correlation coefficients, (ρ_{U4} and $\rho_{U0.095}$) of the U4 and U0.095 subsamples and the respective probabilities, $P = P(\rho \geq \rho_{pearson})$ generated by chance in a random distribution, are presented in Table 2, (Dainotti et al. 2011).

Fig. 1b, illustrates the trend in a few tested 'prompt-afterglow' distributions to increase the correlation coefficient with selecting the GRBs with the most accurate determination of the plateau phase parameters, as measured by the error parameter u. The same trend was presented earlier Dainotti et al. (2010) for the afterglow ($\log L^*_a$, $\log T^*_a$) distribution. On the figure, e.g., we have data derived for 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 8 GRBs left for the limiting $u = 0.095$. The prompt emission parameters E_{iso}, $< L^*_p >_{90}$ and $< L^*_p >_{Tp}$ tested versus the afterglow luminosity L^*_a show significant correlations (cf. Table 2, and its full version in Table 2 Online Material, Dainotti et al. (2011)), but one should note that the mean prompt emission luminosity, $< L^*_p >_{45}$, derived using the characteristic time scale T_{45}, provides the slightly higher value of the Spearman correlation coefficient for small u data points. One may also note that the correlations involving the considered mean prompt emission luminosities are higher that the one involving the isotropic energy E_{iso}.

The GRB energy flux of the prompt emission phase is highly non-uniform, non-evenly distributed within the time T_{90} or T_p, as compared to T_{45}. Thus selecting different characteristic time scales to derive the mean prompt luminosity is equivalent to considering different physical phases of the prompt emission variation. T_{45} puts greater emphasis on the peaks of the luminosity, while T_{90} including periods when the emission is low or absent puts therefore more weight on the total elapsed time of the activity period.

We conclude that the error parameter u reveals a number of strict relations between GRBs observational parameters, otherwise partly hidden within large scattered samples involving all available events. In the considered standard GRBs the mechanism causing the prompt phase of the burst influences directly the afterglow plateau phase Troja et al. (2007).

4. Conclusions

In this Letter we present new significant correlations between the characteristic luminosity of the afterglow plateau phase, L^*_a, and the parameters which characterize the prompt emission, including the mean luminosities and the integral emitted energy. For the afterglow light curves which are well fitted by the Willingale's phenomenological model, with most accurately determined L^*_a and T^*_a values, we find tight prompt-afterglow correlations in the analyzed distributions. Thus, 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 a number of the well fitted light curves, not a simple increase of the total number of GRBs with know redshifts.

Correlations between the physical properties of the prompt emission and the luminosity of the afterglow plateau reveals that mean (averaged in time) energetic properties of the prompt emission more directly influence the afterglow plateau phase as compared to E_{iso}, providing new constraints for the physical model of the GRB explosion mechanism. The ($L^*_a, < L^*_p >_{45}$) correlation could suggest that the burst and afterglow arise from the same relativistic ejecta, if the energy of those ejecta determines the luminosity of both the prompt and of the afterglow phases. Following such an interpretation we have also studied the correlation between the burst prompt and afterglow plateau characteristic energies, E_{iso} vs. E_a (where $E_a = L^*_a \cdot T_a$), with a resulting weaker correlation: for U4 sample of 62 GRBs the Spearman correlation coefficient is 0.39, while for the U0.095 sample of 8 GRBs it is 0.42.

No significant prompt-afterglow correlations were detected for the sample of IC GRBs, but the small number of registered events unable one to draw any firm conclusion about existence or not of such correlations for the well fitted IC light curve shapes.

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