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Ten years of *Swift*: a universal scaling for short and long gamma-ray bursts ($E_{X,iso}$-$E_{\gamma,iso}$-E_{pk})

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From the comprehensive statistical analysis of *Swift* X-ray light-curves collected from the launch of the *Swift* satellite until the end of 2010, we found a three parameter correlation between the isotropic energy emitted in the rest frame 1-10^4 keV energy band during the prompt emission ($E_{\gamma,iso}$), the rest frame peak of the prompt emission energy spectrum (E_{pk}), and the X-ray energy emitted in the rest frame 0.3-30 keV observed energy band ($E_{X,iso}$). The importance of this scaling law is that it is followed by both long and short GRBs, and, at the same time, involves prompt and afterglow emission quantities. Therefore there are some properties which are shared by long and short GRBs as a whole. We updated this correlation considering all GRBs observed until June 2014, confirming the existence of this scaling law, and examining some particular GRBs, as 090426 and 100816A. We also discuss the physics that is driving this correlation.

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1. Introduction

The *Swift* satellite [1], launched on November 2004, opened a new era for the study and understanding of gamma-ray busts (GRBs), detecting more than 900 GRBs until now. Thanks to its data, many correlations involving prompt and afterglow emission quantities were investigated (e.g. [2, 3, 4, 5, 6]).

From the comprehensive statistical analysis of *Swift* X-ray light-curves collected from December 2004 until December 2010 ([7], hereafter M13), we found a three-parameter correlation between the isotropic energy emitted in the rest frame 1-10^4 keV energy band during the prompt emission ($E_{\gamma,iso}$), the rest frame peak of the prompt emission energy spectrum (E_{pk}), and the X-ray energy emitted in the rest frame 0.3-30 keV observed energy band ($E_{X,iso}$). The uniqueness of this correlation is that accommodates long, short, and low-energetic GRBs, and, at the same time, involves prompt and afterglow emission quantities, suggesting that there are some properties which are shared by the GRB class as a whole ([8], hereafter B12, M13).

We considered all GRBs observed until June 2014 as in M13 and we selected only GRBs that have: i) secure redshift measurement; ii) measured E_{pk}; iii) complete X-ray light-curve[1]. In this way, we obtained a new sample composed of 81 long GRBs, 12 short GRBs and 2 GRBs with uncertain classification[2]. The new sample contains $\sim$35% more GRBs than the previous one; in particular the sample of short GRBs doubled (Table 1).

Uncertainties are given at 68 per cent confidence level (c.l.) unless explicitly mentioned. Standard cosmological quantities have been adopted: $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_\Lambda = 0.7$ and $\Omega_M = 0.3$.

2. The three-parameter correlation

The three-parameter correlation (Figure 1) involves $E_{X,iso}$, $E_{\gamma,iso}$, and E_{pk}. E_{pk} and $E_{\gamma,iso}$ are calculated as described in [3]. For short GRBs 080123, 090423, 100625A, 111117A, and 130603B, we consider the values of E_{pk} and $E_{\gamma,iso}$ reported in [9]. $E_{X,iso}$ is the X-ray energy emitted in the 0.3-30 keV band in the rest frame and we calculated it as in M13 (for more details see also [10, 11]).

The correlation is derived using the method of D'Agostini [12], which considers an intrinsic scatter σ_{ext} that accounts for the possible contribution of hidden variables. We obtained:

$$\mathrm{Log}\left[\frac{E_{X,iso}}{\mathrm{erg}}\right] = (0.97\pm0.06)\,\mathrm{Log}\left[\frac{E_{\gamma,iso}}{\mathrm{erg}}\right] -(0.57\pm0.13)\,\mathrm{Log}\left[\frac{E_{pk}}{\mathrm{keV}}\right]-(0.62\pm0.08), \tag{2.1}$$

with an extra-scatter $\sigma_{ext} = 0.32\pm0.04$. Figure 1 shows a two-dimension representation of this relation respect to observations. As explained in previous papers (B12, M13), this correlation is

[1] Promptly re-pointed by *Swift*/XRT (t_{rep} < 300 s) and for which observations were not limited by any observing constraint (M13).

[2] GRBs with uncertain classification are GRB 090426 and GRB 100816A. A detailed discussion can be found in Sec. 3.

Table 1: List of 34 GRBs added to the old sample. Short GRBs are marked in boldface, while GRB with uncertain clssification is underlined.

GRB name
080123, 090426, **100117A**, **100625A**, 110106B, 110205A, 110213A, 110503A, 110715A, 110731A, 110801A, 110818A, 111107A, **111117A**, 111209A, 111228A, 120119A, 120326A, **120804A**, 120712A, 120802A, 120811C, 121128A, 130408A, 130427A, 130505A, **130603B**, 130701A, 130831A, 130907A, 130925A, 131030A, 140206A, 140419A

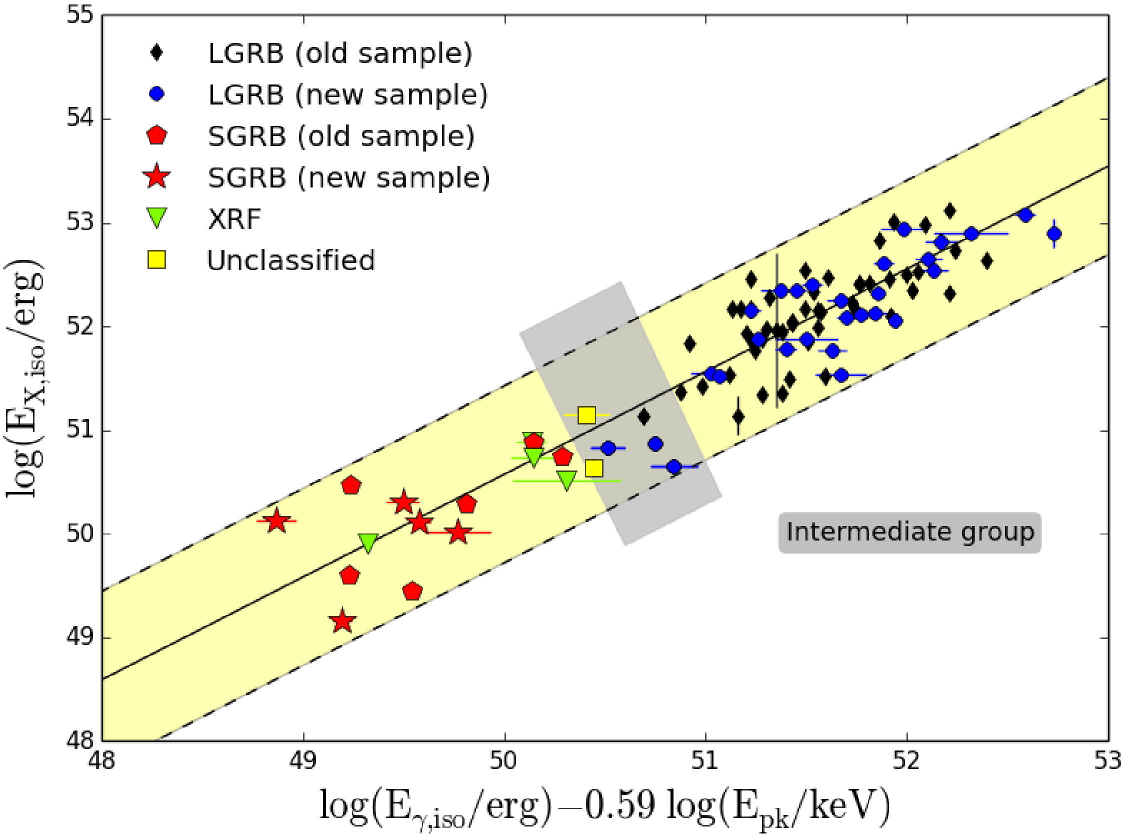

Figure 1: Three-parameter correlation for the sample of 81 long GRBs (*black diamonds* for the old sample, *blue dots* for the new sample, and *green triangles* for low-energetic GRBs (i.e. X-ray flashes (XRFs), GRBs with $E_{\gamma,iso} \lesssim 10^{52}$ erg), 12 short GRBs (*red pentagons* for the old sample and *red stars* for the new sample), and two GRBs with uncertain classification (*yellow squares*). The *black solid line* is the best-fitting function y = 0.99 (x - 0.59 z) - 0.63 and the *yellow area* marks the 2σ region. The *gray area* indicates the intermediate group.

robust, spanning four orders of magnitude in $E_{X,iso}$ and E_{pk}, and six orders of magnitude in $E_{\gamma,iso}$, and combines both short and long GRBs in a common scaling.

3. The intermediate group

In the previous version of the three-parameter correlation, there was a gap between short and long GRBs. Due to the updated sample, now this area is occupied by three new long GRBs

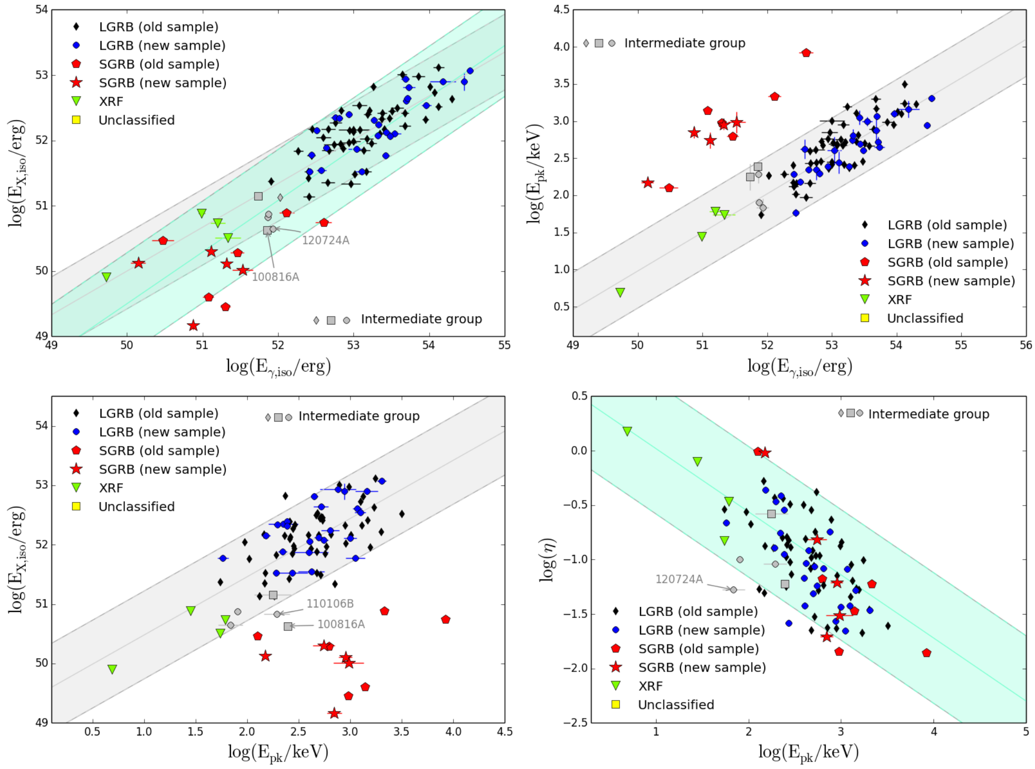

Figure 2: *Lightblue* and *gray solid lines* are the best-fitting functions, while *gray* and *lightblue areas* mark the 2σ region for the best fit function obtained for the sample of long GRBs and the complete sample, respectively. The name of the outlier GRBs is indicated. *Top left*, $E_{\gamma,iso}$ - $E_{X,iso}$ relation: Log Y = 0.82 Log X - 0.85 (σ=0.39) (all GRBs); Log Y = 0.67 Log X - 0.66 (σ=0.35) (long GRBs). *Top right*, $E_{\gamma,iso}$ - E_{pk} relation: Log Y = 0.52 Log X + 0.02 (σ=0.18) (long GRBs). *Bottom left*, E_{pk} - $E_{X,iso}$ relation: Log Y = 1.00 Log X - 0.68 (σ=0.34) (long GRBs). *Bottom right*, E_{pk} - ε relation: Log Y = 0.62 Log X - 0.65 (σ=0.35) (all GRBs).

(110806B, 120724A, 130831A), two GRBs with uncertain classification (090426, 100816A), and a long GRB belonging to the old sample (080916) (Figure 1, gray area).

In particular, analysing the two-parameter correlation between $E_{X,iso}$, $E_{\gamma,iso}$ and E_{pk} (Figure 2), respectively, we notice that:

1. GRBs 090426, 080916, and 130831A behave as long GRBs. Indeed, 080916 and 130831A are characterized by a $T_{90} > 2$ s and a soft spectrum; moreover, a supernova was detected in association with GRB 130831A [13]. These two GRBs have also a redshift < 1. The classification of GRB 090426 is debated (e.g., [14, 15, 16, 17, 18, 9]).

2. The other three GRBs show a lower X-ray energy respect that is expected for long GRBs having their E_{pk} or $E_{\gamma,iso}$, respectively.

For a GRB event, the efficiency of the process is defined as the ratio between the prompt emission energy and the outflow kinetic energy (e.g., [19]). Since the kinetic energy could be computed considering the afterglow emission, we define the inverse of the efficiency as $\varepsilon = E_{\gamma,iso}$

/ $E_{X,iso}$ and we plot this quantity against the peak energy E_{pk} (Figure 2, bottom right). As we showed in our previous works (B12, M13), we have two new groups: one of low-energetic GRBs which are less efficient and occupy the top left part of the plane, and the other group composed of short and long GRBs, which have similar efficiencies. From this plot we can see that GRBs of the intermediate group share the area with efficient bursts.

4. Physics and models

The photospheric model considers how the GRB spectrum in the optically thick phase can be modified by the interaction of the radiation field with the leptonic component of the outflow, before it is released at the photosphere [20, 21, 22, 23]. The simulations made by Lazzati et al. [24] can reproduce the three-parameter correlation since the radiative efficiency of brighter bursts is higher than that of weaker bursts. However, for adequately comparing the observations and the simulations, it is necessary to assume a value for the electron equipartition parameter ε [24]. They show that by adopting the fiducial value $\varepsilon = 0.1$, a good agreement between the simulation results and the observed values is obtained.

In the Cannonball (CB) model [25, 26, 27], the Inverse Compton scattering caused by the interaction between electrons of the CB plasma and the light in the near ambient of the supernova is responsible of the gamma-ray prompt emission of GRBs, while the afterglow emission is related to the synchrotron radiation of electrons swept-in and accelerated in the CBs. In this model, the three-parameter correlation is simply the combination of the two parameter correlations of kinetic origin that are followed by both long and short GRBs, even if with different normalizations, and so it depends on the large Doppler boosting and the relativistic beaming that strongly influenced the observed radiation [28].

5. Summary and conclusions

In this work we updated the three-parameter correlation (B12, M13) considering GRBs detected until June 2014: the new sample contains about 35% more GRBs than the original one, and, in particular, the number of short GRBs doubles (81 long GRBs, 12 short GRBs, and 2 GRBs with uncertain classification). Due to the increment of the number of bursts in our sample, the area between long and short GRBs is filled by three new long GRBs, two GRBs with uncertain classification, and a GRB belonging to the old sample. For a better understanding of the properties of these six intermediate GRBs, we considered also the two parameter correlations involving $E_{X,iso}$, $E_{\gamma,iso}$ and E_{pk}. From this analysis, for instance, we found out that GRB 090426 lies in the group of long GRBs, despite the short duration of its gamma-ray emission, and GRB 100816A shows a low X-ray energy respect that of long GRBs. Moreover, GRBs of the intermediate group are efficient as long and short GRBs. The three-parameter correlation can be a useful tool for classifying GRBs and understanding their properties as a group. Finally, we briefly report the role of the three parameter correlation in the photospheric model [24] and in the Cannonball model [28]. A detailed description and analysis of the three-parameter correlation and its implications will be presented in Zaninoni et al. (in preparation).

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