The $E_{\text{peak}} - E_{\text{iso}}$ relation revisited with *Fermi* GRBs

Resolving a long-standing debate?★

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ABSTRACT

Aims. We used a sample of gamma-ray bursts (GRBs) detected by *Fermi* and *Swift* to reanalyze the correlation discovered by Amati et al. (2002, A&A, 390, 81) between E_{pi} , the peak energy of the prompt GRB emission, and E_{iso} , the energy released by the GRB assuming isotropic emission. This correlation has been disputed by various authors, and our aim is to assess whether it is an intrinsic GRB property or the consequence of selection effects.

Methods. We constructed a sample of *Fermi* GRBs with homogeneous selection criteria, and we studied their distribution in the $E_{\text{pi}} - E_{\text{iso}}$ plane. Our sample is made of 43 GRBs with a redshift and 243 GRBs without a redshift. We show that GRBs with a redshift follow a broad $E_{\text{pi}} - E_{\text{iso}}$ relation, while GRBs without a redshift show several outliers. We use these samples to discuss the impact of selection effects associated with GRB detection and with redshift measurement.

Results. We find that the $E_{\text{pi}} - E_{\text{iso}}$ relation is partly due to intrinsic GRB properties and partly due to selection effects. The lower right boundary of the $E_{\text{pi}} - E_{\text{iso}}$ relation stems from a true lack of luminous GRBs with low E_{pi} . In contrast, the upper left boundary is attributed to selection effects acting against the detection GRBs with low E_{iso} and large E_{pi} that appear to have a lower signal-to-noise ratio. In addition, we demonstrate that GRBs with and without a redshift follow different distributions in the $E_{\text{pi}} - E_{\text{iso}}$ plane. GRBs with a redshift are concentrated near the lower right boundary of the $E_{\text{pi}} - E_{\text{iso}}$ relation. This suggests that it is easier to measure the redshift of GRBs close to the lower $E_{\text{pi}} - E_{\text{iso}}$ boundary and that GRBs with a redshift follow the Amati relation better than the general population. In this context, we attribute the controversy about the reality of the Amati relation to the complex nature of this relation resulting from the combination of a true physical boundary and biases favoring the detection and the measurement of the redshift of GRBs located close to this boundary.

Key words. gamma-ray burst: general – cosmology: miscellaneous

1. Introduction

Gamma-ray bursts (GRBs) are powerful cosmic explosions that are visible up to high redshifts ($z > 5$; Lamb & Reichart 2000; Boër et al. 2006; Bloom et al. 2009; Vedrenne & Atteia 2009). GRBs have two phases: a very bright flash of high-energy radiation usually lasting several seconds (sometimes also seen in visible light), called the prompt emission, followed by a long-lasting decaying afterglow, visible at longer wavelengths during several hours to months. This behavior is understood as the manifestation of a transient relativistic jet pointing towards the Earth, with the prompt emission being released inside the jet and the afterglow resulting from the interaction of the jet with the surrounding medium. The prompt emission is usually recorded with wide-field gamma-ray imagers or spectrometers and the afterglow with follow-up telescopes in space and on the ground. One essential element of GRB observations is the measurement of their redshift, which is done with visible or near infrared spectrographs on large ground-based telescopes. Most often, this measurement relies on the identification of absorption lines from the host galaxy in the spectrum of the afterglow, while it is bright

enough. After measuring the redshift of a GRB one can correct from cosmological effects and infer its *intrinsic* properties.

A surprising result obtained by Amati et al. (2002) was the discovery of a strong correlation between E_{pi} , the peak energy of the νF_{ν} spectrum of the prompt emission at the source, and E_{iso} , the energy released by a GRB assuming isotropic emission. This correlation was first observed on a sample of ten GRBs with a redshift and well measured spectral parameters (Amati et al. 2002). After this discovery, the validity of this $E_{\text{pi}} - E_{\text{iso}}$ relation (often called Amati relation) has been widely discussed, with conflicting results (e.g. Band & Preece 2005; Ghirlanda et al. 2005; Nakar & Piran 2005; Sakamoto et al. 2006; Butler et al. 2007; Cabrera et al. 2007; Schaefer & Collazzi 2007; Butler et al. 2009; Firmani et al. 2009; Krimm et al. 2009; Butler et al. 2010; Shahmoradi & Nemiroff 2011; Collazzi et al. 2012; Kocevski 2012; Goldstein 2012). Despite these discussions, the $E_{\text{pi}} - E_{\text{iso}}$ relation was quickly proposed as a tool to infer GRB redshifts (Atteia 2003), to constrain the physics of the prompt emission (Eichler & Levinson 2004; Rees & Mészáros 2005) and the geometry of GRB jets (Lamb et al. 2005; Toma et al. 2005), and to *standardize* GRBs, in much the same way as the Phillips relation was used to standardize SNe Ia (Phillips 1993). This last approach aims at constructing standard candles with GRBs and at using them to constrain the cosmological parameters (e.g. Dai et al. 2004; Friedman & Bloom 2005; Ghirlanda et al. 2006).

★ Appendix A is available in electronic form at <http://www.aanda.org>

One difficulty of the study of the $E_{\text{pi}} - E_{\text{iso}}$ relation is the need to measure both the peak energy of the $\nu F\nu$ spectrum (called E_{po} in the observer's frame, and E_{pi} in the source frame) and the redshift. The simultaneous operation of *Swift* and *Fermi* since July 2008 (Gehrels et al. 2004; Atwood et al. 2009; Meegan et al. 2009) has provided a new sample of bursts whose parameters are available, allowing exploring the $E_{\text{pi}} - E_{\text{iso}}$ relation over a larger parameter space than it was previously possible (see also Amati 2010). This paper discusses the distribution in the plane $E_{\text{pi}} - E_{\text{iso}}$ of 43 GRBs with a redshift and 243 GRBs without a redshift, all events having E_{po} measured with *Fermi*/GBM. The GRB samples are presented in Sect. 2. The distribution in the plane $E_{\text{pi}} - E_{\text{iso}}$ is discussed in Sect. 3. The impact of selection effects on this distribution is addressed in Sects. 4 and 5, this last section addressing more specifically the selection effects associated with the measurement of redshift. The main results of our study and their interpretation are summarized in Sect. 6.

In all this paper we use a flat Λ CDM cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega_\Lambda = 0.7$, since these values allow the direct comparison of our results with those of Nava et al. (2012). Calculations of luminosity distances are done using the analytical approximation of Wickramasinghe & Ukwatta (2010) that has an accuracy better than 0.3% in the redshift range used in this paper.

2. GRB sample

We select events with well measured spectral parameters from the *Fermi* GRB spectral catalog of Goldstein et al. (2012; see also Paciesas et al. 2012) that provides the spectral parameters of 482 GRBs between GRB 080714086 and GRB 100709602 (about two years of data). We parametrize GRB spectra with the Band function (Band et al. 1993) that consists of two smoothly connected power laws. Following standard naming, we call α the photon spectral index of the low-energy power law ($\alpha > -2$), and β the photon spectral index of the high-energy power law ($\beta < -2$). The $\nu F\nu$ spectrum peaks at the energy E_{peak} , near the junction of the two power laws. The selection is made with the application of the following cuts:

- First, we make a selection on the duration. We consider GRBs with T_{90} between 2 and 1000 s. This criterion excludes short GRBs ($T_{90} < 2$ s), and very long GRBs that are superimposed on a varying background and whose E_{peak} is difficult to measure accurately.
- Second, we require accurate spectral parameters. We exclude GRBs with one or more spectral parameters missing. We exclude GRBs with an error on α (the low-energy index of the Band function) larger than 0.4. We exclude a few GRBs with $\alpha < -2.0$, and GRBs with $\beta > \alpha$ because such values suggest a confusion between fitting parameters. We exclude GRBs with large errors on E_{po} , defined by a ratio of the 90% upper limit to the 90% lower limit larger than 3. We have less stringent constraints on β (the high-energy index of the Band function) since we have checked that the position of GRBs in the $E_{\text{pi}} - E_{\text{iso}}$ plane changes very little with β . When the error on β in the catalog is lacking or larger than 1.0, we assign to β the classical value of -2.3 and we give no error. In a few cases, the high energy spectral index in the *Fermi* catalog is > -2 , and the catalog gives the energy of a spectral break that is not E_{po} . In these cases we look for E_{po} in the GCN Circulars, and if we cannot find it, we simply

Fig. 1. *Fermi* GRBs in the plane $E_{\text{pi}} - E_{\text{iso}}$. The black symbols show 43 GRBs with a redshift and the black solid lines show the corresponding best fit $E_{\text{pi}} - E_{\text{iso}}$ relation with its two sigma limits. Black circles are 34 GRBs detected simultaneously by *Fermi*/GBM and *Swift*/BAT. Black triangles are nine GRBs detected simultaneously by *Fermi*/GBM and another positioning instrument (usually *Fermi*/LAT). The purple circles indicate GRBs whose redshift has been measured with the emission lines of the host galaxy. The green and red lines show the possible positions of GRBs without a redshift when they are placed at distances ranging from $z = 0.34$ (leftmost point) to $z = 4.35$ (rightmost point). Red lines indicate GRBs that are beyond the two sigma limit of the $E_{\text{pi}} - E_{\text{iso}}$ relation at any redshift. The dotted blue lines show the best fit $E_{\text{pi}} - E_{\text{iso}}$ relation of Nava et al. (2012) with its two sigma limits. The dashed blue lines show the best fit $E_{\text{pi}} - E_{\text{iso}}$ relation of Amati (2006) with its two sigma limits.

remove the burst from the sample. This procedure suppresses one GRB with a redshift and ten GRBs without a redshift.

267 bursts pass the cuts, 24 with a measured redshift. This is a small number, so we extend the sample of GRBs with a redshift with the addition of 19 *Fermi* GRBs found in GCN circulars that respect the same selection criteria. In the end, we have two samples: 43 GRBs with a redshift, and 243 GRBs without one. GRBs in each sample are listed in Tables A.1 and A.2. The redshifts span the range [0.34–4.35], with a median value $\bar{z} = 1.71$, smaller than the median redshift of *Swift* GRBs ($\bar{z} = 2.14$), measured by Jakobsson et al. (2012).

3. The $E_{\text{pi}} - E_{\text{iso}}$ relation of *Fermi* GRBs

3.1. GRBs with a redshift

Figure 1 shows with black symbols the locations of 43 *Fermi* GRBs with a redshift in the $E_{\text{pi}} - E_{\text{iso}}$ plane. These bursts show a clear correlation between E_{pi} and E_{iso} , as for the previous missions. The coefficient of correlation is 0.70, and the best fit correlation is $E_{\text{pi}} = 118 E_{52}^{0.486} \text{ keV}$, where E_{52} is the GRB isotropic energy in units of 10^{52} ergs (the best fit correlation is obtained by weighting each point quadratically by its error on E_{pi}). This will be the definition of the $E_{\text{pi}} - E_{\text{iso}}$ relation in the rest of this paper.

This relation is close to the one found by Gruber et al. (2012) from a sample of *Fermi* GRBs ($E_{\text{pi}} = 120 E_{52}^{0.55} \text{ keV}$), and by Nava et al. (2012) for a larger sample including GRBs from *Fermi* and other missions ($E_{\text{pi}} = 119 E_{52}^{0.554} \text{ keV}$). If we freeze the slope to its best-fit value (0.486), we can compute the vertical standard deviation of data points around the fit: $\text{sigma} = 0.34$

(if we measure the standard deviation perpendicular to the best fit line, we get $\sigma = 0.21$). The two-sigma limits are shown in Fig. 1, they are defined by $E_{\text{pi}} = 24 E_{52}^{0.486}$ keV for the lower limit, and $E_{\text{pi}} = 575 E_{52}^{0.486}$ keV, for the upper limit. Figure 1 evidences a broadening of the two sigma confidence region with respect to the relation of Amati (2006) for pre-*Fermi* GRBs that had a vertical sigma = 0.21. This broadening was already noted by Nava et al. (2012) and by Gruber et al. (2012), who measure sigma = 0.34 along the vertical axis, equivalent to the value found here.

3.2. GRBs without a redshift

The green and red dashed lines in Fig. 1 represent the possible locations of GRBs without a redshift in the $E_{\text{pi}} - E_{\text{iso}}$ plane, considering that their redshift may vary between 0.34 and 4.35, the extreme values measured for GRBs with a redshift. We plot in green GRBs lying within the two sigma limits of the $E_{\text{pi}} - E_{\text{iso}}$ relation for some redshifts, and in red the bursts that remain outside these boundaries at any redshift.

For most of the redshift range [0.34–4.35], the green and red lines are nearly parallel to the $E_{\text{pi}} - E_{\text{iso}}$ relation, allowing assessing the position of GRBs without redshifts with respect to this relation. First, we note a clear asymmetry between GRBs above and below the best fit $E_{\text{pi}} - E_{\text{iso}}$ relation. While GRBs with a redshift are more or less symmetric with respect to the best fit $E_{\text{pi}} - E_{\text{iso}}$ relation (22 above and 21 below), the situation is markedly different for GRBs without a redshift. 72% of them lie entirely above the best fit $E_{\text{pi}} - E_{\text{iso}}$ relation, 22% cross it, and 6% only lie entirely below it. This asymmetry is accompanied by a lack of events in the lower right corner of the plot. Since GRBs in this region have large E_{iso} and low E_{pi} , they should have plenty of photons and we cannot attribute their deficit to selection effects. We conclude that GRBs with a large E_{iso} and a low E_{pi} are intrinsically rare.

We finally note that 29 GRBs are located outside the two sigma limits of the $E_{\text{pi}} - E_{\text{iso}}$ relation at all redshifts, all of them lie *above* the two sigma upper limit of the $E_{\text{pi}} - E_{\text{iso}}$ relation. This is larger than the number of six GRBs expected on a purely statistical basis (assuming a gaussian shape of the distribution around the $E_{\text{pi}} - E_{\text{iso}}$ relation). It is difficult to infer the exact significance of this excess, because our definition of the two-sigma limits is rather arbitrary and the uncertainties on E_{peak} make difficult evaluating the true number of outliers. Despite these uncertainties, it is not possible to move more than a few outliers within the two-sigma limits, and we conclude safely that *Fermi* GRBs without a redshift include a significant fraction of outliers to the $E_{\text{pi}} - E_{\text{iso}}$ relation.

At this point we are facing two results: on one hand GRBs with a redshift seem to follow a broad $E_{\text{pi}} - E_{\text{iso}}$ relation, while on the other hand the overall GRB population shows a fraction of outliers of 12% in a region of the plane where GRBs are difficult to detect, suggesting a much broader distribution in the $E_{\text{pi}} - E_{\text{iso}}$ plane. The following sections discuss how the observed $E_{\text{pi}} - E_{\text{iso}}$ distribution is affected by selection effects. In Sect. 4 we discuss selection effects on GRB detection, while in Sect. 5 we discuss selection effects on the measurement of the redshift.

4. Study of the outliers

In the rest of this paper, we call *outliers* GRBs located above the two-sigma limit of the $E_{\text{pi}} - E_{\text{iso}}$ relation. There are 33 outliers, four GRBs with a redshift, and 29 GRBs without a redshift,

Fig. 2. Distribution of three classes of GRBs (see Fig. 1) in a photon fluence – peak photon flux plane. Several outliers to the $E_{\text{pi}} - E_{\text{iso}}$ relation (in red) are GRBs at the limit of detection, with low photon fluence and peak photon flux.

Table 1. Comparison of the observed properties of 33 GRBs incompatible with $E_{\text{pi}} - E_{\text{iso}}$ relation at all redshifts (*outliers*) with 253 GRBs that are within two sigma of the $E_{\text{pi}} - E_{\text{iso}}$ relation (*others*).

Parameter (unit)	Median (outliers)	Median (others)	KS significance
T_{90} (s)	22.5	29.7	0.17
Alpha	−0.88	−0.89	0.93
Beta	−2.30	−2.30	0.49
E_{po} (keV)	715	151	3.5×10^{-16}
Photon Fluence (ph cm ^{−2})	10.8	53.7	6.2×10^{-7}
Energy Fluence (10 ^{−7} erg cm ^{−2})	28	74	1.4×10^{-3}
Peak Photon Flux (ph cm ^{−2} s ^{−1})	3.2	5.5	2.5×10^{-3}

Notes. The KS significance gives the probability that a parameter has the same distribution for outliers and for other GRBs.

they are shown in boldface in Tables A.1 and A.2. In this section we compare the properties of the 33 outliers, with those of the remaining 253 GRBs, in order to understand whether they are affected by significant selection effects. Table 1 shows the results of Kolmogorov-Smirnov (KS) tests comparing the duration T_{90} , spectral parameters, and brightness between the two classes. Outliers differ from GRBs that follow the $E_{\text{pi}} - E_{\text{iso}}$ relation by their E_{po} and their brightness: on average, outliers have larger E_{po} (a median E_{po} of 715 keV vs. 151 keV) and a smaller fluence (a median fluence of 28×10^{-7} erg cm^{−2} vs. 74×10^{-7} erg cm^{−2}). These differences are clearly visible in Fig. 3 that shows the cumulative distribution functions (CDF) of these parameters: on average outliers have an observed E_{peak} four times larger and a photon fluence five times smaller than other GRBs.

The main consequence is that outliers are much more difficult to detect (see Band 2003, for a discussion of GRB sensitivity

Fig. 3. Cumulative distribution function (CDF) of 3 GRB parameters: E_{po} , photon fluence, and peak photon flux for the three classes of *Fermi* GRBs defined in Fig. 1. Black solid line: 43 GRBs with a redshift; green dashed line: 253 GRBs with or without a redshift that may be compatible with the $E_{pi} - E_{iso}$ relation at some redshift; red dash-dotted line: 29 GRBs without a redshift that are incompatible with the $E_{pi} - E_{iso}$ relation at any redshift (outliers). This figure emphasizes the larger E_{po} and smaller photon fluence of outliers.

of different detectors). In fact, it is difficult to assess the true extension of the GRB population above the $E_{pi} - E_{iso}$ relation because GRBs in this region have fewer photons as the direct consequence of their large E_{po} . The fraction of outliers found here is thus a lower limit of the true fraction of outliers. We conclude that, above the $E_{pi} - E_{iso}$ relation, the observed GRB distribution is currently limited by the sensitivity of gamma-ray detectors.

Similar conclusions were reached by Nakar & Piran (2005), Goldstein et al. (2010), and Shahmoradi & Nemiroff (2011) based on BATSE GRBs, by Butler et al. (2007) based on *Swift* GRBs and by Collazzi et al. (2012) based on various GRB samples from pre-*Fermi* missions, and by Kocevski (2012) based on a synthetic GRB population. Other authors have stressed the role of selection effects, however they consider that they have little impact on the $E_{pi} - E_{iso}$ relation. Ghirlanda et al. (2008) show that the existence of an $E_{po} - \text{fluence}$ correlation could impact the $E_{pi} - E_{iso}$ relation of *Swift* GRBs and that pre-*Swift* GRBs also could be affected by unknown selection effects, and Nava et al. (2008) states that, although selection effects are present, they do not determine the spectral-energy correlations. In order to clarify this debate, we now compare the distribution of GRBs with a redshift and GRBs without a redshift in the $E_{pi} - E_{iso}$ plane.

5. GRBs with a redshift

In order to compare GRBs with a redshift and GRBs without a redshift, we discuss the differences between the two classes in terms of their observed properties in Sect. 5.1, and in terms of their intrinsic properties in Sect. 5.2. We limit the sample of GRBs with a redshift to the bursts that have the same selection criteria as GRBs without a redshift, that is to a sample of 34 GRBs detected *simultaneously* by *Fermi*/GBM (for the spectral parameters) and *Swift*/BAT (for the localization). This excludes nine GRBs detected and localized by *Fermi*/LAT, IPN, or INTEGRAL that were outside the field-of-view of *Swift*/BAT at the time of the burst. Including these events in the sample of GRBs with a redshift would artificially increase the fraction of very bright GRBs, biasing the comparison between *Fermi* GRBs with and without a redshift, as explained in Sect. 5.3 below.

5.1. Observed properties

Table 2 compares the properties of GRBs with a redshift with the population of GRBs with no redshift. GRBs with a redshift

Table 2. Comparison of the observed properties of 34 GRBs with a redshift and 243 GRBs without a redshift.

Parameter (unit)	Median (with z)	Median (without z)	KS significance
T_{90} (s)	43.5	28.2	0.10
Alpha	-0.92	-0.87	0.58
Beta	-2.30	-2.30	0.58
E_{po} (keV)	142	162	0.44
Photon Fluence (ph cm $^{-2}$)	88	40	7.3×10^{-4}
Energy Fluence (10^{-7} erg cm $^{-2}$)	108	58	1.4×10^{-3}
Peak Photon Flux (ph cm $^{-2}$ s $^{-1}$)	7.7	4.7	6.4×10^{-2}

Notes. The KS significance gives the probability that a parameter has the same distribution for GRBs with a redshift and GRBs without a redshift.

differ from the general population by their larger brightness (fluence and peak flux). This is not surprising since GRBs that are brighter in gamma-rays are also expected to be brighter in visible (e.g. Wanderman & Piran 2010). The larger average fluence and peak flux of GRBs with a redshift is explained in part by a smaller distance (the median redshift of our sample is $\bar{z} = 1.71$, compared $\bar{z} = 2.14$ for *Swift* GRBs.) and in part by a greater ease to measure the redshift of brighter GRBs. This effect however cannot create the $E_{pi} - E_{iso}$ relation that is an intrinsic property of GRBs. It is thus necessary to check whether the measurement of the redshift biases the intrinsic properties of GRBs, and more specifically their distribution in the $E_{pi} - E_{iso}$ plane.

5.2. Intrinsic properties

In order to check whether the measurement of the redshift impacts the distribution of GRBs in the $E_{pi} - E_{iso}$ plane, we use the following procedure: from the sample of 243 GRBs without a redshift, we randomly select 34 GRBs, we assign them the redshifts of the 34 GRBs with measured redshifts, and we compute their E_{pi} , E_{iso} , and the slope of the best fit $E_{pi} - E_{iso}$ relation. We repeat this procedure 1000 times and we compare the median values of E_{pi} , E_{iso} , and the slope of the $E_{pi} - E_{iso}$ relation with

Fig. 4. Comparison of simulated GRB populations. *Left panel.* E_{pi} as a function of E_{iso} . *Right panel.* Slope of the $E_{\text{pi}} - E_{\text{iso}}$ relation as a function of E_{iso} . Green: *Fermi* GRBs with no redshift not localized by *Swift*/BAT; purple: *Fermi* GRBs with no redshift localized by *Swift*/BAT; blue: *Fermi* GRBs with a redshift localized by *Swift*/BAT; black: *Fermi* GRBs with a redshift, irrespective of the satellite used for the localization. The crosses show the median values and the corresponding error, measured from 1000 simulated samples. The point symbols show the values measured for two actual samples: in blue 34 GRBs studied in Sect. 5.2, and in black the full sample of 43 GRBs with a redshift.

those of GRBs with redshifts. We apply the same procedure to the subsample of 34 GRBs with a redshift, in order to understand how the redshift redistribution impacts the results. For sake of completeness, we study two additional distributions: 25 *Fermi* GRBs localized by *Swift* without a redshift, and the full sample of 43 GRBs with a redshift. The results are summarized in Fig. 4. The crosses show the median E_{iso} , E_{pi} , the median slope of the $E_{\text{pi}} - E_{\text{iso}}$ relation and the one-sigma error on these values, for the four simulated GRBs samples. The blue and black symbols show the values measured for GRBs with a redshift (excluding or not the GRBs detected by *Fermi*/LAT).

These simulations bring the following results:

- The compatibility (within errors) of the green and purple crosses shows that the localization with *Swift*/BAT does not bias the distribution of E_{pi} or E_{iso} .
- The comparison of the blue and green crosses shows that GRBs with a redshift have slightly larger E_{iso} (median $= 9.2 \times 10^{52}$ erg vs. 4.8×10^{52} erg), similar E_{pi} (median $= 345$ keV vs. 440 keV), and slopes of the $E_{\text{pi}} - E_{\text{iso}}$ relation that are compatible (~ 0.3). The measurement of the redshift thus favors GRBs that are more energetic, with large E_{iso} .
- The comparison of the simulated populations (blue and black crosses) with the actual GRBs (blue and black symbols) shows that the redshift redistribution builds simulated populations that have more or less the same E_{iso} and E_{pi} as the original population, but a significantly smaller slope of the $E_{\text{pi}} - E_{\text{iso}}$ relation. This difference can be attributed to the fact that, unlike real GRBs, simulated GRBs can occupy the empty region in the lower right corner of the $E_{\text{pi}} - E_{\text{iso}}$ plane, decreasing the slope of the correlation.

The differences pointed here between GRBs with a redshift and GRBs without a redshift concern average values of the parameters. They provide no information on the joint distribution in the plane $E_{\text{pi}} - E_{\text{iso}}$ for the two groups. A look at Fig. 1 suggests different distributions of the two groups, with GRBs with a redshift gathered closer to the $E_{\text{pi}} - E_{\text{iso}}$ boundary. To verify this hypothesis, we have divided our GRB sample (34 GRBs with a redshift plus 243 GRBs without a redshift) into four subsamples according to their distance to the $E_{\text{pi}} - E_{\text{iso}}$ boundary

(for GRBs with a redshift) or to their smallest distance to this line (for GRBs without a redshift). Since we have excluded the nine GRBs with a redshift detected by *Fermi*/LAT, each subsample includes eight or nine GRBs with a redshift. We have computed the fraction of GRBs with a redshift in each subsample, obtaining the following numbers with increasing distance from the boundary: $9/44 = 0.20$; $9/42 = 0.21$; $8/68 = 0.12$; and $8/123 = 0.065$. These numbers clearly show that GRBs with a redshift do not follow the general GRB distribution in the plane $E_{\text{pi}} - E_{\text{iso}}$, being more concentrated near the $E_{\text{pi}} - E_{\text{iso}}$ boundary. This is illustrated in Fig. 5 that shows with different colors the groups of GRBs at different distances from the $E_{\text{pi}} - E_{\text{iso}}$ boundary.

With this observation, we finally get a coherent picture of the origin of $E_{\text{pi}} - E_{\text{iso}}$ relation. This correlation can be attributed to the combination of two effects: a physical boundary in the plane $E_{\text{pi}} - E_{\text{iso}}$, and biases favoring the detection and the measurement of redshift of GRBs located along this boundary. We have evidenced two biases acting in the same direction. First, for a given E_{iso} , GRBs far from the $E_{\text{pi}} - E_{\text{iso}}$ boundary have fewer gamma-ray photons, making their detection and localization with gamma-ray detectors more difficult. This is confirmed with the computation of V/V_{max} as a proxy for the signal-to-noise ratio¹. We find that the median V/V_{max} increases with the distance from the $E_{\text{pi}} - E_{\text{iso}}$ boundary, with median $(V/V_{\text{max}}) = 0.28-0.35-0.51-0.75$ for the 4 groups of GRBs with a redshift defined in the previous paragraph. These numbers only concern a small fraction of GRBs but they clearly show that GRBs close to the $E_{\text{pi}} - E_{\text{iso}}$ boundary have larger signal-to-noise and are more easily detected.

The second bias is connected with the measurement of the redshift: we have found that the fraction of GRBs with a redshift increases close to the $E_{\text{pi}} - E_{\text{iso}}$ boundary. This suggests the existence of a bias that makes easier the measurement of the redshift when a GRB is close to the $E_{\text{pi}} - E_{\text{iso}}$ boundary. Since the capability to measure the redshift is closely linked with the optical

¹ V/V_{max} is a number between 0 and 1 that represents the position of a GRB within its “volume of detectability”. GRBs with a low signal-to-noise ratio that are close to the detection limit have $V/V_{\text{max}} \lesssim 1$; in contrast GRBs with a large signal-to-noise ratio have $V/V_{\text{max}} \approx 0$.

Fig. 5. GRBs classification in 4 groups according to their distance to the $E_{\text{pi}} - E_{\text{iso}}$ boundary. The parameter used to separate the 4 groups is their vertical distance (for GRBs with a redshift) or their smallest vertical distance (for GRBs without a redshift) to the black line. The black line has a slope = 0.486, assumed to be the slope of the $E_{\text{pi}} - E_{\text{iso}}$ boundary. The position of the black line is arbitrary, it does not impact the groups as long as it stays below the GRB sample.

brightness of the afterglow, we infer that there are factors enhancing the optical luminosity of GRBs close to the $E_{\text{pi}} - E_{\text{iso}}$ boundary. The verification of this hypothesis requires a systematic study of the optical luminosity of GRB afterglows, which is beyond the scope of this paper. This bias contributes to further reduce the width of the distribution of GRBs with a redshift. As a consequence of these two biases, GRBs with a redshift appear preferentially along a narrow band above the $E_{\text{pi}} - E_{\text{iso}}$ boundary, giving rise to correlation found by [Amati et al. \(2002\)](#).

5.3. Bright GRBs detected with LAT and IPN

Figure 1 shows that the 9 GRBs that were not localized by *Swift* (the black triangles) concentrate in the upper right of the $E_{\text{pi}} - E_{\text{iso}}$ relation, increasing the significance of the correlation. In our interpretation, these very bright GRBs cannot have low E_{pi} because of the $E_{\text{pi}} - E_{\text{iso}}$ boundary. Since their brightness facilitates the measurement of their redshift, they play an important role in shaping the $E_{\text{pi}} - E_{\text{iso}}$ relation.

This is also the case of GRB 130427A (the rightmost point in Figs. 2 and 5) that is one of the few nearby energetic GRBs (like GRB 030329 detected by HETE-2 at $z = 0.17$, [Vanderspek et al. 2004](#)). GRB 130427A is at redshift $z = 0.34$, the value of V/V_{max} for this GRB, $V/V_{\text{max}} = 0.003$, indicates that there is a 10% chance observing this GRB so close among 30 similar bursts at higher redshift. Considering that *Fermi* has detected more than 1100 GRBs from its launch to the end of April 2013, the detection of a nearby energetic GRB like GRB 130427A is not unexpected. Interestingly, GRB 130427A lies perfectly along the Amati relation ([Amati et al. 2013](#)). This is compatible with our interpretation that highly energetic bursts cannot have low E_{pi} because of the $E_{\text{pi}} - E_{\text{iso}}$ boundary.

6. Discussion

The results presented in this paper are based on the distribution of GRBs in the plane $E_{\text{pi}} - E_{\text{iso}}$. We discuss below some

selection effects that may affect this distribution. First, it is not possible to measure E_{po} outside the energy range of the detector. This restricts the range of measured E_{po} to [30–1300] keV. These bounds prevent us to include X-Ray Flashes (soft GRBs with $E_{\text{peak}} < 30$ keV) in our analysis but they do not bias the distribution of GRBs in the $E_{\text{pi}} - E_{\text{iso}}$ plane and the conclusions of our analysis. Second, we have studied the impact of the errors on E_{po} and on the energy fluence S_{γ} given in Table A.2. If we systematically replace E_{po} with $E_{\text{po}} - \sigma_{E_{\text{po}}}$ for all GRBs without a redshift, the number of outliers decreases from 29 to 18. Similarly, if we change the fluence S_{γ} with $S_{\gamma} - \sigma_{S_{\gamma}}$ for all GRBs without a redshift, the number of outliers decreases from 29 to 28. Thus, we cannot get rid of the outliers, even with this rather drastic method.

Two additional effects, acting in opposite directions, can affect the observed distribution in the $E_{\text{pi}} - E_{\text{iso}}$ plane. First, GRBs in the upper left part of the plot are more difficult to detect because they have intrinsically fewer photons than GRBs closer to the Amati relation. Since this bias acts against the detection of outliers, it leads to underestimate the true fraction of outliers, as explained in Sect. 4. On the other hand, it is possible to “create” outliers from GRBs following the Amati relation if the measurements of E_{pi} or E_{iso} are strongly biased. One possibility is the “duration bias” discussed by [Kocevski & Petrosian \(2013\)](#). This bias results from the inability of count-limited instruments to detect the parts of GRBs with low count rates, artificially reducing T_{90} and E_{iso} of faint GRBs. The duration bias may also affect the measurement of E_{peak} since the brightest parts of faint GRBs are often those with the largest E_{peak} . Since Table 1 shows that outliers have essentially the same duration distribution as the rest of GRBs, there is no hint in the data of a strong duration bias that could significantly alter our analysis. We have also checked the possible biases on E_{peak} with the measurement of the ratio $\text{RE} = E_{\text{peak}}(\text{at peak})/E_{\text{peak}}(\text{average})$ for outliers and for other GRBs. We find that RE is broadly distributed with median(RE) = 0.74 ± 0.30 for outliers, median(RE) = 1.14 ± 0.28 for other GRBs, and median(RE) = 1.06 ± 0.28 for GRBs with a redshift. These numbers show that outliers are only marginally affected by selection effects that could modify their E_{peak} . Overall, we found no bias capable of “creating” the observed outliers from GRBs that follow the $E_{\text{pi}} - E_{\text{iso}}$ relation.

The main conclusion of this paper is that the $E_{\text{pi}} - E_{\text{iso}}$ relation is due to the combination of two effects: a physical limit that prevents the existence of GRBs with a large E_{iso} and a low E_{pi} (creating an $E_{\text{pi}} - E_{\text{iso}}$ boundary), and the sensitivity of gamma-ray and optical imagers that strongly favor the detection and localization of GRBs located close to the $E_{\text{pi}} - E_{\text{iso}}$ boundary (see also [Shahmoradi & Nemiroff 2011](#)). The combination of these two effects creates a band in the $E_{\text{pi}} - E_{\text{iso}}$ plane where GRBs are more easily detected, and a thinner band where their redshift can be measured. We believe that this interpretation explains the apparently contradictory results obtained by people who have checked the validity of $E_{\text{pi}} - E_{\text{iso}}$ relation either using large samples of GRBs without a redshift or only using GRBs with a redshift. The first have consistently found large fractions of outliers dismissing the relation (e.g. [Band & Preece 2005](#); [Nakar & Piran 2005](#); [Butler et al. 2007, 2010](#); [Shahmoradi & Nemiroff 2011](#); [Collazzi et al. 2012](#)), while the second usually confirmed its validity (e.g. [Ghirlanda et al. 2005](#); [Sakamoto et al. 2006](#); [Krimm et al. 2009](#); [Nava et al. 2012](#)). The horizontal extent of the $E_{\text{pi}} - E_{\text{iso}}$ relation depends on the GRB luminosity function, on the evolution of the GRB rate with redshift, and on the volume of detection for each type of GRB. We have checked that the leftmost

part of the $E_{\text{pi}} - E_{\text{iso}}$ relation contains mainly faint GRBs with low E_{pi} detected at low redshift ($z < 1$), while the rightmost part is made of luminous GRBs with large E_{pi} that can only be found in large volumes of observation (except GRB 130427A discussed in Sect. 5.3). Finally, we note that similar studies could be performed with other relations, like the $E_{\text{pi}} - L_{\text{iso}}$ relation (Yonetoku et al. 2004) or the $E_{\text{pi}} - E_{\gamma}$ relation (Ghirlanda et al. 2004), to check their nature and their validity.

A discussion of the origin of the $E_{\text{pi}} - E_{\text{iso}}$ boundary is beyond the scope of this paper. If it is a consequence of the dominant radiation mechanism at work in GRBs, as we expect, theoretical studies may help understanding the nature and the true location of this boundary (see for instance Eichler & Levinson 2004; Yamazaki et al. 2004; Rees & Mészáros 2005; Thompson et al. 2007; Giannios 2012; Mochkovitch et al. 2012; Beniamini & Piran 2013; Shahmoradi 2013, for explanations within the framework of different theoretical or phenomenological models). The observation of an $E_{\text{pi}} - E_{\text{iso}}$ relation in time-resolved spectra (e.g. Ghirlanda et al. 2010; Frontera et al. 2012; Basak & Rao 2012; Lu et al. 2012) may also provide insights into the origin of the $E_{\text{pi}} - E_{\text{iso}}$ boundary. Finally, Since the $E_{\text{pi}} - E_{\text{iso}}$ relation is not an intrinsic property of GRBs, it may be difficult to use it to standardize GRBs (Ghirlanda et al. 2006; Mészáros & Gehrels 2012). This might nevertheless be possible if one finds a way of identifying GRBs close to the $E_{\text{pi}} - E_{\text{iso}}$ boundary, thanks to their temporal properties (e.g. spectral lags) or to the characteristics of their afterglows.

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³ <http://raunvis.hi.is/~pja/GRBsample.html>

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Appendix A: Data tables

The following tables provide the names and the spectral properties of the 286 GRBs used in this study, extracted from the *Fermi* GRB catalog of Goldstein et al. (2012).

Table A.1. 43 GRBs with a redshift.

GRB Name	z^*	α	α error	$\beta^{\dagger}$	β error	E_{po}^{**} (keV)	E_{po} error	Fluence, S_{γ} (10^{-7} erg cm $^{-2}$)	Fluence error
GRB 080804972	2.20 ^a	-0.52	0.09	-1.90	0.08	218 ^{bu}	25	91.3	1.1
GRB 080810549	3.35 ^b	-1.16	0.03	-2.30		834 ^{bu}	125	108.2	0.5
GRB 080905705	2.37 ^c	-0.85	0.23	-2.28	0.62	179 ^{bu}	60	29.1	0.4
GRB 080916009	4.35 ^d	-1.08	0.01	-2.15	0.07	662 ^{bu}	45	602.7	0.7
GRB 080916406	0.69 ^e	-0.90	0.10	-2.30		109 ^{bb}	9	78.1	0.8
GRB 081008832	1.97 ^f	-1.01	0.12	-2.09	0.21	166 ^{bu}	36	103.2	1.5
GRB 081121858	2.51 ^g	-0.43	0.13	-2.09	0.09	161 ^{bu}	17	152.7	2.2
GRB 081221681	2.26 ^h	-0.90	0.02	-3.86	0.49	87 ^{bu}	1	300.4	0.9
GRB 081222204	2.77 ⁱ	-0.86	0.05	-2.31	0.12	142 ^{bu}	10	118.9	1.0
GRB 090102122	1.55 ^j	-0.94	0.02	-2.30		417 ^{bu}	18	279.1	0.6
GRB 090323002	3.57 ^k	-1.29	0.01	-2.45	0.18	639 ^{bu}	41	1180.9	1.7
GRB 090328401	0.74 ^l	-1.13	0.01	-2.65	0.26	1458 ^{bu}	74	420.2	0.7
GRB 090424592	0.54 ^m	-1.04	0.02	-2.76	0.13	154 ^{bu}	4	463.2	0.4
GRB 090516353	4.11 ⁿ	-1.52	0.05	-2.30	0.27	142 ^{bu}	26	172.2	0.6
GRB 090618353	0.54 ^o	-1.26	0.06	-2.50	0.33	156 ^{bc}	11	2684.5	4.3
GRB 090902462	1.82 ^p	-1.00	0.00	-2.30		1044 ^{bu}	17	2217.9	3.2
GRB 090926181	2.11 ^q	-0.85	0.01	-2.39	0.04	336 ^{bu}	6	1465.7	3.4
GRB 090926914	1.24 ^r	0.13	0.12	-3.25	0.34	82 ^{bu}	3	107.9	1.5
GRB 091003191	0.90 ^s	-1.07	0.02	-2.22	0.11	366 ^{bu}	27	233.2	0.8
GRB 091020900	1.71 ^t	-1.26	0.06	-2.30		246 ^{bu}	36	83.5	1.5
GRB 091127976	0.49 ^u	-1.26	0.07	-2.22	0.02	35 ^{bu}	2	207.3	0.4
GRB 091208410	1.06 ^v	-1.44	0.07	-2.32	0.47	124 ^{bd}	20	61.9	1.9
GRB 100414097	1.37 ^w	-0.62	0.01	-3.53	0.48	664 ^{bu}	16	884.7	1.9
GRB 100615083	1.40 ^x	-1.24	0.08	-2.27	0.12	86 ^{be}	8	87.2	0.8
GRB 100728095	1.57 ^y	-0.75	0.01	-3.04	0.57	344 ^{bf}	9	1278.8	5.8
GRB 100728439	2.11 ^z	-0.80	0.20	-2.20	0.20	104 ^{bu}	14	33.4	0.6
GRB 100814160	1.44 ^{aa}	-0.64	0.14	-2.02	0.12	106 ^{bh}	14	149.4	0.9
GRB 100906576	1.73 ^{ab}	-1.34	0.08	-1.98	0.07	106 ^{bi}	18	232.9	0.6
GRB 101213451	0.41 ^{ac}	-1.10	0.07	-2.35	0.72	310 ^{bj}	49	74.0	1.0
GRB 101219686	0.55 ^{ad}	0.33	0.36	-2.12	0.12	70 ^{bk}	8	39.9	0.5
GRB 110731465	2.83 ^{ae}	-0.80	0.03	-2.98	0.30	304 ^{bl}	13	228.9	0.6
GRB 111228657	0.71 ^{af}	-1.90	0.10	-2.70	0.30	34 ^{bm}	3	181.4	0.6
GRB 120119170	1.73 ^{ag}	-0.98	0.03	-2.36	0.09	189 ^{bn}	8	386.7	1.4
GRB 120326056	1.80 ^{ah}	-0.98	0.14	-2.53	0.15	46 ^{bo}	4	32.6	0.5
GRB 120711115	1.41 ^{ai}	-0.94	0.01	-2.40	0.04	973 ^{bp}	35	1942.8	2.3
GRB 120716712	2.49 ^{aj}	-1.00	0.08	-2.08	0.07	114 ^{bq}	12	146.9	0.5
GRB 120811649	2.67 ^{ak}	-0.71	0.20	-2.30		54 ^{br}	3	34.5	2.1
GRB 120907017	0.97 ^{al}	-0.75	0.25	-2.30		154 ^{bs}	33	8.1	0.4
GRB 120909070	3.93 ^{am}	-1.30	0.10	-2.30		370 ^{bt}	140	98.5	1.5
GRB 121128212	2.20 ^{an}	-0.80	0.12	-2.41	0.10	62 ^{bu}	5	104.0	4.0
GRB 121211574	1.02 ^{ao}	-0.30	0.34	-2.30		96 ^{bu}	13	4.8	0.5
GRB 130420313	1.30 ^{aq}	-1.00	0.13	-2.30		56 ^{bu}	3	115.9	2.4
GRB 130427324	0.34 ^{ar}	-0.79	0.00	-3.06	0.02	830 ^{bx}	5	24 620.0	12.4

Notes. ^(†) When β is unconstrained, we use $\beta = -2.3$. The references for the redshift and spectral parameters are given below. The 9 GRBs in italic have been localized by LAT, IPN or INTEGRAL, they are at the bright end of the GRB luminosity function. four GRBs are outliers to the Amati relation, they are indicated in bold. The errors are given for a confidence level of 90%.

References. ^(*) References for the redshift: ^(a) Cucchiara et al. (2008c); Thoene et al. (2008) – ^(b) Burenin et al. (2008); de Ugarte Postigo et al. (2008); Prochaska et al. (2008) – ^(c) Vreeswijk et al. (2008) – ^(d) Greiner et al. (2009) – ^(e) Fynbo et al. (2008) – ^(f) D’Avanzo et al. (2008); Cucchiara et al. (2008a) – ^(g) Berger & Rauch (2008) – ^(h) Salvaterra et al. (2012) – ⁽ⁱ⁾ Cucchiara et al. (2008b); Graham et al. (2008) – ^(j) Cucchiara & Fox (2009); de Ugarte Postigo et al. (2009b) – ^(k) Chornock et al. (2009) – ^(l) Cenko et al. (2009a) – ^(m) Chornock et al. (2009); Wiersema et al. (2009a) – ⁽ⁿ⁾ de Ugarte Postigo et al. (2009a); Rossi et al. (2009) – ^(o) Cenko et al. (2009b); Fatkhullin et al. (2009) – ^(p) Cucchiara et al. (2009c) – ^(q) Malesani et al. (2009) – ^(r) Fynbo et al. (2009) – ^(s) Cucchiara et al. (2009b) – ^(t) Xu et al. (2009) – ^(u) Cucchiara et al. (2009a); Thoene et al. (2009) – ^(v) Perley et al. (2009); Wiersema et al. (2009b) – ^(w) Cucchiara & Fox (2010) – ^(x) Kruehler et al. (2013b) – ^(y) Kruehler et al. (2013a) – ^(z) Flores et al. (2010) – ^(aa) O Meara et al. (2010) – ^(ab) Tanvir et al. (2010) – ^(ac) Chornock & Berger (2011) – ^(ad) de Ugarte Postigo et al. (2011); Sparre et al. (2011) – ^(ae) Tanvir et al. (2011) – ^(af) Cucchiara & Levan (2011); Dittmann et al. (2011); Palazzi et al. (2011); Schulze et al. (2011); Xu et al. (2011) – ^(ag) Cucchiara & Prochaska (2012); Milisavljevic et al. (2012); Pancoast et al. (2012) – ^(ah) Tello et al. (2012) – ^(ai) Tanvir et al. (2012b) – ^(aj) D’Elia et al. (2012); Greiner et al. (2012) – ^(ak) Fynbo et al. (2012); Thoene et al. (2012) – ^(al) Sanchez-Ramirez et al. (2012) – ^(am) Hartoog et al. (2012) – ^(an) Tanvir et al. (2012a) – ^(ao) Perley et al. (2012) – ^(ap) Cucchiara & Fumagalli (2013) – ^(aq) de Ugarte Postigo et al. (2013) – ^(ar) Flores et al. (2010); Garnavich (2013); Levan et al. (2013); Xu et al. (2013). ^(**) References for the peak energy: ^(ba) Goldstein et al. (2012) – ^(bb) Bissaldi et al. (2008) – ^(bc) McBreen (2009a) – ^(bd) McBreen (2009b) – ^(be) Foley & Briggs (2010) – ^(bf) von Kienlin (2010a) – ^(bg) von Kienlin (2010b) – ^(bh) von Kienlin (2010c) – ^(bi) Gruber (2010a) – ^(bj) Gruber (2010b) – ^(bk) van der Horst (2010) – ^(bl) Gruber (2011) – ^(bm) Briggs & Younes (2011) – ^(bn) Gruber (2012) – ^(bo) Collazzi (2012) – ^(bp) Gruber & Pelassa (2012) – ^(bq) Gruber & Goldstein (2012) – ^(br) Xiong & Meegan (2012) – ^(bs) Younes & Barthelmy (2012) – ^(bt) Chaplin (2012) – ^(bu) McGlynn (2012) – ^(bv) Yu (2012) – ^(bw) Xiong & Rau (2013) – ^(bx) von Kienlin (2013).

Table A.2. 243 GRBs without a redshift.

GRB Name	α	α error	β^a	β error	E_{po}^{**} (keV)	E_{po} error	Fluence, S_γ (10^{-7} erg cm $^{-2}$)	Fluence error
GRB 080715950	-1.10	0.08	-2.30	0.35	230	42	50.4	0.8
GRB 080723557	-0.76	0.03	-2.15	0.04	200	8	722.3	2.5
GRB 080723985	-0.93	0.03	-2.30		431	22	307.9	2.1
GRB 080724401	-0.91	0.09	-2.10	0.08	104	10	156.9	0.5
GRB 080727964	-0.94	0.09	-2.49	0.36	180	24	133.0	0.8
GRB 080730786	-0.75	0.06	-2.30		135	6	63.5	0.8
GRB 080803772	-0.47	0.13	-2.30		298	45	43.9	0.7
GRB 080804456	-1.09	0.13	-2.30		196	43	80.0	0.9
GRB 080805496	-1.82	0.14	-2.30		31	12	17.5	0.5
GRB 080806896	-0.66	0.15	-2.34	0.08	47	3	132.8	1.9
GRB 080807993	-0.92	0.06	-2.30		618	118	73.0	0.9
GRB 080808565	-1.11	0.10	-2.44	0.19	80	8	39.7	0.4
GRB 080809808	-1.26	0.31	-2.20	0.22	63	21	41.4	0.5
GRB 080812889	-0.18	0.30	-2.18	0.31	145	29	24.5	0.4
GRB 080816503	-0.87	0.05	-2.61	0.20	126	7	133.0	0.8
GRB 080816989	-0.54	0.10	-2.30		1561	285	33.0	0.9
GRB 080817161	-0.93	0.02	-2.10	0.06	354	19	532.5	0.7
GRB 080818579	-1.47	0.09	-2.30		236	83	38.0	0.6
GRB 080818945	-1.43	0.13	-2.30		68	9	17.4	0.2
GRB 080821332	-0.76	0.11	-2.58	0.30	110	11	35.9	0.2
GRB 080824909	-1.11	0.11	-2.25	0.29	143	29	27.3	0.6
GRB 080825593	-0.65	0.03	-2.30	0.07	174	6	341.9	1.0
GRB 080829790	-0.83	0.13	-2.30		75	5	25.2	0.2
GRB 080830368	-1.05	0.08	-2.30		269	55	70.0	1.1
GRB 080904886	-0.76	0.24	-2.51	0.08	31	2	52.4	0.7
GRB 080905570	-0.99	0.16	-2.74	0.48	74	9	40.9	0.6
GRB 080906212	-0.52	0.10	-2.06	0.09	125	11	58.7	1.4
GRB 080913735	-0.27	0.18	-2.30		102	8	35.4	0.9
GRB 080924766	-1.20	0.18	-2.05	0.14	84	23	47.3	0.8
GRB 080925775	-1.08	0.04	-2.09	0.08	163	14	184.7	0.4
GRB 081006604	-0.32	0.37	-1.99	0.40	538	247	8.3	0.2
GRB 081009140	-1.53	0.02	-4.12	0.45	31	0	383.0	0.5
GRB 081012549	-0.10	0.23	-2.30		326	57	45.1	1.1
GRB 081017474	-0.85	0.31	-2.30		66	10	13.9	0.2
GRB 081021398	0.19	0.24	-2.78	0.42	127	12	57.4	0.8
GRB 081024851	-1.11	0.09	-2.30		83	7	62.7	0.7
GRB 081025349	-0.44	0.14	-2.21	0.33	255	41	63.2	1.2
GRB 081028538	-0.75	0.17	-3.08	0.65	67	6	22.7	0.3
GRB 081101532	-0.72	0.04	-2.30		524	33	150.8	3.5
GRB 081102739	-0.90	0.11	-2.30		134	15	37.6	0.9
GRB 081118876	-0.75	0.13	-2.23	0.09	64	6	49.4	0.4
GRB 081122520	-0.80	0.07	-2.51	0.35	197	20	75.4	0.8
GRB 081125496	-0.51	0.06	-2.37	0.11	161	9	185.4	1.3
GRB 081126899	-0.78	0.05	-2.30		325	26	114.5	0.7
GRB 081129161	-1.04	0.06	-2.28	0.24	259	34	161.9	1.5
GRB 081130629	-0.98	0.11	-2.30		174	26	32.2	0.6
GRB 081206275	0.13	0.37	-2.20	0.40	151 ^{ca}	29	38.6	0.6
GRB 081206987	-1.04	0.22	-2.30		262	113	11.3	0.3
GRB 081207680	-0.59	0.03	-2.08	0.08	416	24	486.2	1.0
GRB 081215784	-0.78	0.01	-2.29	0.05	442	13	546.7	0.6
GRB 081215880	-0.29	0.28	-2.59	0.38	116	16	17.8	0.4
GRB 081217983	-0.73	0.07	-2.45	0.26	163	15	96.2	1.4
GRB 081224887	-0.77	0.02	-2.30		401	13	375.7	1.7
GRB 081226156	-1.30	0.39	-2.05	0.07	36	13	39.5	0.2
GRB 081231140	-1.17	0.04	-1.96	0.07	242	31	161.2	1.2

Notes. The spectral parameters are from (Goldstein et al. 2012), except otherwise indicated. 29 GRBs are outliers to the Amati relation, they are indicated in italic. The errors are given for a confidence level of 90%. ^(**) References for the spectral parameters: ^(ca) von Kienlin (2008).

Table A.2. continued.

GRB Name	α	α error	β^d	β error	E_{po}^{**} (keV)	E_{po} error	Fluence (10^{-7} erg cm $^{-2}$)	Fluence error
GRB 090101758	-1.10	0.05	-2.30		107	6	122.9	1.1
GRB 090112332	-1.41	0.07	-2.30		276	73	39.2	0.7
GRB 090112729	-0.75	0.06	-2.43	0.14	139 ^{cb}	9	92.3	1.1
GRB 090113778	-1.20	0.19	-2.06	0.29	137	58	15.7	0.5
GRB 090117632	-1.37	0.06	-2.04	0.25	350	117	119.4	2.0
GRB 090126227	-1.27	0.20	-2.30		44	5	11.0	0.2
GRB 090129880	-1.49	0.08	-2.12	0.23	171	53	55.7	0.6
GRB 090131090	-1.18	0.07	-2.19	0.04	54	4	175.2	0.7
GRB 090202347	-1.31	0.06	-2.30		570 ^{cc}	170	49.5	0.3
GRB 090207777	-1.19	0.10	-2.30		371	108	24.1	0.4
GRB 090217206	-0.94	0.02	-2.30		673	41	275.2	0.3
GRB 090222179	-0.97	0.14	-2.56	0.66	148 ^{cd}	27	32.3	0.5
GRB 090227310	-0.92	0.07	-1.92	0.16	1678	565	28.6	0.2
GRB 090228976	-0.76	0.26	-2.30		142	34	9.6	0.7
GRB 090301315	-1.05	0.13	-2.09	0.47	480	213	22.7	0.4
GRB 090306245	-0.85	0.23	-2.30		97	16	13.7	0.4
GRB 090307167	-0.63	0.37	-2.30		153	47	10.9	0.4
GRB 090310189	-0.87	0.11	-2.84	0.89	123	15	55.4	0.6
GRB 090316311	-1.15	0.18	-2.30		136	34	10.6	0.2
GRB 090319622	-0.84	0.14	-2.26	0.28	152	27	60.3	0.6
GRB 090327404	-0.42	0.18	-2.47	0.21	84	8	28.2	0.6
GRB 090330279	-0.81	0.07	-2.04	0.11	203	23	118.1	0.4
GRB 090403314	-1.11	0.19	-2.30		222	85	10.9	0.2
GRB 090411991	-0.74	0.12	-1.98	0.11	172	29	62.1	0.9
GRB 090413122	-0.83	0.18	-1.99	0.33	304	108	32.3	0.5
GRB 090419997	-1.38	0.05	-2.30		150	14	95.4	2.4
GRB 090425377	-1.29	0.11	-2.03	0.05	69 ^{ce}	11	181.3	1.5
GRB 090426690	-1.26	0.10	-2.10	0.38	281	107	35.4	0.9
GRB 090428441	-0.46	0.22	-2.30		84	8	10.4	0.6
GRB 090502777	-0.78	0.29	-2.36	0.14	48	7	35.0	0.3
GRB 090509215	-0.89	0.17	-2.42	0.80	206	57	54.2	0.7
GRB 090511684	-0.77	0.28	-1.93	0.29	167	72	24.9	0.8
GRB 090513916	-0.87	0.11	-2.30		813	241	49.4	1.8
GRB 090514726	-0.57	0.20	-2.13	0.26	189	41	22.5	0.3
GRB 090514734	-1.23	0.14	-2.24	0.18	85	16	95.5	2.1
GRB 090516137	-0.99	0.04	-2.12	0.17	328	39	168.4	1.8
GRB 090518244	-0.64	0.17	-2.74	0.53	105	13	21.1	0.7
GRB 090519462	-0.59	0.39	-2.30		98	24	43.8	0.5
GRB 090520850	-0.71	0.10	-2.30		215	24	33.2	1.0
GRB 090520876	-0.92	0.13	-2.76	0.15	41	2	61.8	0.4
GRB 090524346	-1.00	0.05	-2.68	0.20	95	5	165.9	0.6
GRB 090528173	-0.55	0.24	-2.24	0.06	40	4	65.6	1.1
GRB 090528516	-1.23	0.02	-2.14	0.08	229	17	435.2	0.9
GRB 090529564	-1.18	0.06	-1.91	0.08	205	38	86.9	0.3
GRB 090530760	-0.98	0.03	-2.62	0.05	64	1	598.9	1.6
GRB 090602564	-0.71	0.13	-2.36	0.47	715	197	27.9	0.6
GRB 090610648	-0.79	0.10	-2.30		1905	681	13.5	0.6
GRB 090610723	-0.64	0.22	-2.63	0.61	115	19	39.6	0.6
GRB 090612619	-0.74	0.08	-2.37	0.45	468	77	58.2	0.7
GRB 090620400	-0.43	0.05	-2.72	0.18	160	6	132.6	0.4
GRB 090621185	-1.10	0.20	-2.12	0.09	56 ^{cf}	11	108.4	2.1
GRB 090623107	-0.77	0.05	-2.05	0.14	367	42	118.4	0.7
GRB 090623913	-1.28	0.08	-2.30		221	48	21.6	0.6
GRB 090625560	-0.78	0.21	-2.30		147	27	24.6	0.9
GRB 090626189	-1.29	0.02	-1.98	0.02	175 ^{cg}	12	630.5	1.1

Notes. ^(**) References for the spectral parameters: ^(cb) van der Horst (2009) – ^(cc) von Kienlin (2009a) – ^(cd) von Kienlin (2009b) – ^(ce) von Kienlin (2009c) – ^(cf) Rau (2009) – ^(cg) von Kienlin (2009d).

Table A.2. continued.

GRB Name	α	α error	β^a	β error	E_{po}^{**} (keV)	E_{po} error	Fluence (10^{-7} erg cm $^{-2}$)	Fluence error
GRB 090630311	-1.36	0.14	-2.30		63	7	10.8	0.1
GRB 090703329	-1.19	0.31	-2.19	0.38	87	38	8.5	0.3
GRB 090704242	-1.25	0.06	-2.30		275	47	84.8	1.0
GRB 090709630	-0.49	0.23	-1.96	0.13	106	20	22.1	0.4
GRB 090713020	-0.13	0.11	-3.07	0.31	92	4	94.8	0.4
GRB 090717034	-0.94	0.06	-1.95	0.04	108	8	232.3	0.7
GRB 090718762	-1.11	0.03	-2.47	0.15	162	9	250.2	1.2
GRB 090719063	-0.72	0.02	-3.09	0.27	250	7	468.5	1.6
GRB 090720276	-0.59	0.12	-2.30		105	8	32.2	0.3
GRB 090720710	-1.04	0.04	-2.42	0.35	1242	254	142.4	0.2
GRB 090730608	-0.50	0.20	-2.34	0.35	137	22	31.8	0.8
GRB 090804940	-0.58	0.04	-3.62	0.35	95	2	144.3	1.9
GRB 090805622	-1.00	0.18	-2.30		86	10	57.9	0.5
GRB 090809978	-0.81	0.04	-2.06	0.06	187	12	216.3	1.3
GRB 090810659	-0.84	0.23	-2.36	0.08	38	4	98.9	0.9
GRB 090810781	-0.44	0.34	-2.10	0.07	47	7	51.5	0.6
GRB 090811696	-0.50	0.29	-2.30		685	231	10.5	0.2
GRB 090813174	-1.25	0.14	-2.14	0.12	81	17	33.3	0.4
GRB 090814950	-0.84	0.08	-2.22	0.35	340	60	159.8	3.9
GRB 090815300	-0.40	0.39	-2.30		165	43	14.3	0.4
GRB 090815438	-1.05	0.17	-2.83	0.21	34	2	48.9	1.6
GRB 090815946	-1.00	0.16	-2.30		154	42	28.8	0.3
GRB 090820027	-0.68	0.01	-2.60	0.04	209	3	1536.0	1.8
GRB 090826068	-0.68	0.21	-2.30		163	35	8.5	0.4
GRB 090829672	-1.44	0.04	-2.10	0.10	183 ^{ch}	31	766.4	1.6
GRB 090829702	-0.54	0.15	-2.14	0.17	121	16	48.1	0.6
GRB 090831317	-1.43	0.05	-2.20	0.21	190	38	94.4	0.7
GRB 090902401	0.06	0.20	-2.30		428	54	16.7	0.4
GRB 090904058	-1.13	0.07	-2.30	0.12	113	11	217.1	2.2
GRB 090904581	-0.68	0.20	-2.37	0.97	840	401	16.4	0.3
GRB 090908341	-0.98	0.06	-2.41	0.64	3483	1212	26.0	0.2
GRB 090909487	-1.26	0.23	-2.30		205	88	57.3	2.0
GRB 090910812	-0.87	0.05	-2.77	0.62	284	28	186.6	2.1
GRB 090912660	-0.38	0.23	-2.56	0.34	92	11	103.8	1.7
GRB 090915650	-0.78	0.22	-1.91	0.21	197	66	29.9	0.4
GRB 090917661	-0.77	0.24	-2.30		231	62	10.8	0.4
GRB 090922539	-0.93	0.05	-2.50	0.18	142	9	110.5	0.5
GRB 090922605	-0.94	0.23	-1.86	0.13	306	133	45.1	1.0
GRB 090925389	-0.40	0.19	-2.01	0.09	101	13	89.1	3.1
GRB 090928646	-0.56	0.25	-1.97	0.22	233	70	19.5	0.7
GRB 090929190	-0.48	0.07	-2.30		527	40	81.8	1.0
GRB 091005679	-0.76	0.28	-2.16	0.49	161	57	14.1	0.7
GRB 091010113	-1.10	0.03	-2.30		148	6	99.6	0.6
GRB 091020977	-0.99	0.05	-2.73	0.62	1201	241	107.5	0.6
GRB 091024380	-0.88	0.06	-2.70	0.50	190	18	255.3	0.5
GRB 091030613	-0.66	0.13	-2.56	0.39	149	19	44.8	0.4
GRB 091030828	-0.96	0.03	-2.50	0.29	513	41	296.3	2.0
GRB 091031500	-0.86	0.04	-2.10	0.13	461	50	152.9	0.9
GRB 091101143	-0.78	0.08	-2.40	0.20	127	11	78.4	0.8
GRB 091103912	-1.04	0.09	-2.11	0.18	196	35	56.0	1.1
GRB 091107635	-1.03	0.28	-2.30		165	62	9.3	0.4
GRB 091109895	-1.11	0.16	-2.30		102	17	20.2	0.4
GRB 091112737	-1.10	0.06	-2.22	0.40	683	169	99.0	0.9
GRB 091115177	-0.87	0.12	-2.03	0.41	577	223	15.4	0.6
GRB 091117080	-0.99	0.32	-2.19	0.25	75	23	36.8	0.4

Notes. ^(**) References for the spectral parameters: ^(ch) Wilson-Hodge (2009).

Table A.2. continued.

GRB Name	α	α error	β^a	β error	E_{po} (keV)	E_{po} error	Fluence (10^{-7} erg cm $^{-2}$)	Fluence error
GRB 091120191	-1.07	0.03	-3.22	0.45	124	4	285.3	4.1
GRB 091123081	-0.92	0.31	-2.24	0.33	88	26	21.3	0.9
GRB 091123298	-0.81	0.08	-2.18	0.12	157	15	640.4	3.7
GRB 091128285	-1.01	0.03	-2.30		193	9	403.9	4.5
GRB 091202072	-0.77	0.36	-2.32	0.43	94	27	16.7	0.3
GRB 091202219	-0.95	0.19	-1.96	0.11	101	26	68.0	1.5
GRB 091207333	-0.72	0.13	-2.11	0.18	152	23	53.7	1.1
GRB 091209001	0.29	0.21	-3.04	0.26	62	3	100.3	1.9
GRB 091220442	-1.00	0.11	-2.31	0.15	86	10	58.3	0.5
GRB 091221870	-0.63	0.09	-2.04	0.09	165	17	89.4	2.2
GRB 091223511	0.34	0.24	-2.19	0.16	130	13	86.9	0.5
GRB 091227294	-0.97	0.06	-2.30		287	33	68.9	1.1
GRB 091230712	-0.62	0.22	-2.30		100	13	25.8	0.9
GRB 091231206	-0.72	0.09	-2.64	0.37	151	15	97.6	2.1
GRB 100111176	-1.40	0.16	-2.30		202	98	11.5	0.2
GRB 100116897	-1.03	0.02	-2.30		1075	84	333.9	1.6
GRB 100118100	-0.29	0.23	-2.55	0.76	839	231	14.4	1.1
GRB 100122616	-0.99	0.13	-2.31	0.05	43	3	120.0	1.6
GRB 100130729	-0.99	0.14	-2.10	0.16	153	34	85.7	0.9
GRB 100130777	-1.02	0.10	-1.99	0.12	157	28	138.7	1.7
GRB 100131730	-0.87	0.06	-2.36	0.15	146	11	73.4	0.8
GRB 100201588	-1.37	0.08	-2.13	0.13	107	19	107.2	0.6
GRB 100204024	-0.87	0.06	-2.30		188	15	103.4	1.5
GRB 100204566	-1.10	0.17	-2.69	0.87	125	28	37.8	0.5
GRB 100205490	-0.55	0.22	-2.75	0.85	127	22	13.6	0.3
GRB 100207665	-0.41	0.32	-2.30		357	101	20.8	0.4
GRB 100211440	-0.84	0.07	-2.77	0.23	111	7	151.8	1.7
GRB 100212550	0.31	0.22	-2.41	0.32	283	33	36.0	0.9
GRB 100212588	-0.88	0.34	-2.30		104	24	3.5	0.2
GRB 100218194	-0.76	0.21	-2.30		181	42	26.4	1.0
GRB 100219026	-0.69	0.15	-2.46	0.77	777	266	34.8	0.7
GRB 100224112	-1.35	0.07	-2.61	0.80	166	31	107.2	3.7
GRB 100225115	-0.73	0.08	-2.67	0.88	404	62	58.5	0.8
GRB 100225580	-1.03	0.07	-2.15	0.22	267	45	64.0	1.1
GRB 100225703	-0.56	0.18	-2.06	0.26	497	138	16.1	0.4
GRB 100301223	-0.28	0.16	-2.30		111	8	24.0	0.6
GRB 100304004	-0.87	0.09	-2.30		616	130	63.1	1.4
GRB 100311518	-0.44	0.18	-2.30		321	66	25.7	1.0
GRB 100313288	-0.43	0.13	-2.24	0.24	185	24	44.0	0.8
GRB 100322045	-0.81	0.02	-1.94	0.03	253	11	570.9	2.1
GRB 100323542	-1.00	0.10	-2.30		336	70	20.4	1.3
GRB 100324172	-0.59	0.02	-2.30		446	14	427.9	1.7
GRB 100325275	-0.41	0.14	-2.88	0.74	156	17	33.5	0.4
GRB 100326402	-1.02	0.08	-2.07	0.18	234	42	118.2	2.7
GRB 100330309	-0.93	0.11	-2.41	0.23	103	12	43.0	0.5
GRB 100410740	-0.93	0.08	-2.30		997	298	62.1	3.1
GRB 100413732	-1.22	0.05	-2.30		959	331	104.7	0.8
GRB 100420008	-0.67	0.11	-2.93	0.61	124	11	43.1	0.4
GRB 100423244	-0.88	0.05	-2.16	0.22	1215	260	79.2	1.2
GRB 100424729	-0.60	0.14	-2.59	0.73	273	45	74.1	0.6
GRB 100424876	-0.96	0.05	-2.30		233	20	149.5	1.7
GRB 100427356	-0.78	0.15	-2.93	0.83	104	13	22.8	0.6
GRB 100429999	-0.79	0.17	-2.32	0.54	215	56	27.8	0.4
GRB 100502356	-1.19	0.04	-2.30		508	80	156.0	2.1
GRB 100503554	-0.99	0.05	-2.30		241	21	173.2	4.1
GRB 100504806	-0.59	0.19	-2.30		82	7	23.3	1.3
GRB 100506653	-1.08	0.15	-2.00	0.28	232	90	24.2	0.5
GRB 100507577	0.46	0.11	-3.48	0.55	134	5	99.7	1.2
GRB 100510810	-0.79	0.20	-2.90	0.53	65	7	37.2	0.5
GRB 100511035	-1.38	0.02	-2.25	0.26	1325	304	299.7	1.0

Table A.2. continued.

GRB Name	α	α error	β^d	β error	E_{po}^{**} (keV)	E_{po} error	Fluence (10^{-7} erg cm $^{-2}$)	Fluence error
GRB 100513879	-1.34	0.06	-2.30		238	38	37.1	0.5
GRB 100515467	-1.07	0.08	-2.22	0.17	145	19	61.1	0.5
GRB 100517072	-1.00	0.29	-1.93	0.05	45	11	65.9	0.2
GRB 100517154	-1.11	0.13	-2.30		48	3	27.9	0.3
GRB 100517243	-1.26	0.37	-2.66	0.39	39	6	26.9	0.4
GRB 100517639	-0.36	0.09	-2.30		87	3	29.1	1.3
GRB 100519204	-0.85	0.04	-2.30		108	3	206.8	2.3
GRB 100522157	-1.39	0.09	-2.30		158	27	38.6	0.4
GRB 100530737	-1.16	0.28	-2.31	0.73	107	47	4.8	0.2
GRB 100604287	-1.08	0.12	-2.20	0.23	167	34	55.1	0.4
GRB 100609783	0.32	0.10	-2.30		152	5	174.2	6.1
GRB 100612726	-0.73	0.04	-2.49	0.10	113	4	136.3	3.6
GRB 100614498	-0.91	0.22	-2.21	0.08	41	5	196.3	3.3
GRB 100619015	-1.30	0.07	-2.30		120	12	112.9	0.7
GRB 100701490	-0.85	0.03	-2.24	0.10	1132	114	260.3	0.4
GRB 100704149	-0.93	0.09	-2.00	0.14	175	30	104.0	1.1
GRB 100707032	-0.91	0.02	-2.30		283 ^{ci}	7	877.2	1.6
GRB 100709602	-1.07	0.08	-2.30		183	27	80.8	0.8

Notes. ^(**) References for the spectral parameters: ^(ci) [Wilson-Hodge \(2009\)](#).