Probing the existence of the $E_{\text{peak}}-E_{\text{iso}}$ correlation in long Gamma Ray Bursts

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ABSTRACT

We probe the existence of the $E_{\text{peak}}-E_{\text{iso}}$ correlation in long GRBs using a sample of 442 BATSE bursts with known $E_{\text{peak}}$ and with redshift estimated through the lag–luminosity correlation. This sample confirms that the rest frame peak energy is correlated with the isotropic equivalent energy. The distribution of the scatter of the points around the best fitting line is similar to that obtained with the 27 bursts with spectroscopic redshifts. We interpret the scatter in the $E_{\text{peak}} - E_{\text{iso}}$ plane as due to the opening angle distribution of GRB jets. By assuming that the collimation corrected energy correlates with $E_{\text{peak}}$ we can derive the observed distribution of the jet opening angles, which turns out to be log–normal with a peak value of $\sim 6.5^\circ$.

Key words: cosmology:observations — distance scale — gamma rays: bursts

1 INTRODUCTION

Since the discovery of the cosmological distance scale to Gamma Ray Bursts in 1997 (Djorgovski et al. 1997) several GRB redshifts have been spectroscopically measured$^a$. The small sample of bursts, now comprising 42 events, allowed in the latest years the investigation of the GRB rest frame properties. Several correlations have been discovered between GRBs spectral properties:

(i) the spectral lag - luminosity correlation $\tau - L_{\text{iso}}$ (Norris, Marani & Bonnel 2000; Norris 2002)
(ii) the variability - luminosity correlation $V - L_{\text{iso}}$ (Fenimore & Ramirez–Ruiz 2000; Reichart et al. 2001).
(iii) the peak energy - isotropic energy correlation $E_{\text{peak}} - E_{\text{iso}}$ (Amati et al. 2002; Lloyd & Ramirez-Ruiz 2002). We will call it the Amati correlation.
(iv) the peak energy - isotropic peak luminosity correlation $E_{\text{peak}} - L_{\text{iso,peak}}$ (Yonetoku et al. 2004).
(v) the peak energy - collimation corrected energy correlation $E_{\text{peak}} - E_{\gamma}$ (Ghirlanda, Ghisellini, Lazzati 2004, GGL04 hereafter). We will call it the Ghirlanda correlation.

All these correlations can be represented by powerlaws: their slopes are summarized in Tab. 1. Note that, for the last three correlations, the peak energy $E_{\text{peak}}$ of the $\nu F_{\nu}$ spectrum is obtained by fitting the GRB spectrum time–integrated over the burst duration.

Despite several attempts to explain these correlations (see e.g. Eichler D. & Lenvision A. 2004; Liang E., Dai Z. & Wu X.F. 2004), there is no universally accepted interpretation yet. One of the major drawback of these correlations is that they were found for a small sample of bursts, mainly due to the limited number of reliable redshift measurements. However, one test which can be performed even without knowing the redshift is to check if GRBs with known fluence and $E_{\text{peak}}$ are consistent with – say – the Amati correlation, by considering all possible redshifts.

This kind of consistency check has been performed very recently by two groups which tested the Amati and the Ghirlanda correlation. Nakar & Piran (2004, hereafter NP04) tested the Amati correlation in the observed plane $E_{\text{peak,obs}} - F$ (where $F$ is the burst observed fluence) using a sample of bright BATSE bursts (from Band et al. 1993; Jimenez, Band & Piran 2000). They concluded that $\sim 40\%$ of the BATSE long (bright) bursts are inconsistent with this relation.

Band & Preece (2005, hereafter BP05) extended this work with a larger sample of BATSE GRBs (760 bursts from Mallozzi et al. 1998) and tested both the Amati and the Ghirlanda correlation. They claim that at least $88\%$ of their bursts are inconsistent with the Amati correlation and $1.6\%$ with the Ghirlanda correlation. They also claim that these conclusions are robust, since they are model–independent.

An important point to notice is what is meant by Amati correlation. Originally, Amati et al. (2002) found $E_{\text{peak}} \propto E_{\text{iso}}^{0.5}$ with a small scatter, but using only 9 bursts. Later, GGL04 (see their Tab. 1 and Tab. 2) collected 23 GRBs (including the above 9) with redshift measurements and published peak energy, finding a slightly different slope and, more importantly, a larger scatter around the correlation, whose significance was nevertheless improved (due to the increased number of points). In the same paper, it was demonstrated that for all bursts with a good measurement of the jet opening angle (through the detection of a break in the light curve of the afterglow),

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1 http://www.mpe.mpg.de/~jcg/grbgen.html for a continuously updated table.
the scatter of the Amati correlation was entirely due to the different opening angles of the jet: bursts with the same collimation-corrected energy \(E\) and the same intrinsic \(E_{\text{peak}}\) have different \(E_{\text{iso}}\) because they have different jet opening angles. The scatter of the Amati correlation, far from being due, i.e. to ill-measured quantities, has a physical origin and is revealing of the distribution of the opening angles of the jets.

Bearing this in mind, in this letter we test if \(E_{\text{peak}}\) correlates with \(E_{\text{iso}}\) even if we do expect a large scatter around the best fitting line (if any). To this aim we use a large sample of bursts with “pseudo redshifts” which have been estimated through the lag-luminosity relation (Sec. 2). Having found that indeed the \(E_{\text{peak}}\)-\(E_{\text{iso}}\) correlation exists (Sec. 3), we follow GGL04 and interpret the scatter as due to the distribution of jet opening angles, finding it (Sec. 4). Finally (Sec. 5), we discuss why NP04 and BP05, who also use a large sample of BATSE bursts, arrive to different conclusions.

During the completion of this work, we received a manuscript from Bosnjak et al. By studying the same problem with an independent and complementary approach, they arrive at the same conclusions presented in this letter.

In the following we adopt a standard \(\Lambda\)CDM cosmology with \(\Omega_{\Lambda} = 0.3\), \(\Omega_m = 0.7\) and \(h_0 = 0.7\).

## 2 THE GRB SAMPLE

As described above the Amati correlation involves the peak energy of the time integrated spectrum of the prompt emission. This is obtained by fitting the GRB spectrum time integrated over the entire duration of the burst (see e.g. Band et al. 1993).

Yonetoku et al. (2004; Y04 hereafter) have recently published a catalog of 689 long BATSE GRBs obtained through the spectral analysis of the high spectral resolution BATSE data. The main selection criterium adopted by Y04 is on the peak flux (i.e. \(\geq 2 \times 10^{-7}\) erg cm\(^{-2}\) s\(^{-1}\)). Band, Norris & Bonnell (2004, BNB04 hereafter) derived for the BATSE GRBs in the sample of Mallozzi et al. 1998 (the same used in BP05) their pseudo redshifts through the lag-luminosity correlation (Norris et al. 2000). This sample contains 1165 bursts. We have selected 578 sources contained both in Y04 and in BNB04 to have a sample of bursts with a good measurement of \(E_{\text{peak}}\) and an estimate of their redshift. For each selected burst, we took the fluence from the current BATSE GRB catalog.\(^2\) We excluded from the final sample the sources with particularly large uncertainties on the parameters which are used for the test that we present in the next sections:

- 21 bursts with \(E_{\text{peak}} \leq 40\) keV, since this value is very close to the BATSE threshold, and this makes the fitting procedure highly uncertain (see e.g. Lloyd & Petrosian 2002);
- 5 bursts with errors in \(E_{\text{peak}}\) greater than \(E_{\text{peak}}\) itself;
- 6 bursts with errors on their fluence greater than their fluence.

This sample contains 546 GRBs and it will be used for the test discussed in Sec. 5.

In addition, to the aim of testing the Amati correlation with a sample of GRBs with reliable redshift estimates we excluded:

- 94 bursts with errors in their estimated lag greater than the lag itself;
- 10 bursts with redshift larger than 10.

The final sample contains 442 GRBs and this is used in Sect. 3. Although the estimated pseudo redshifts should be taken with care when considering specific objects, the distribution of redshifts for a large sample of bursts should be more reliable. In Fig. 1 we show that the distribution of the 442 pseudo redshifts of our sample is similar to the distribution of spectroscopically measured redshifts (27 objects). Even if not complete, this sample should be representative of moderately bright BATSE bursts.

## 3 TESTING THE EXISTENCE OF AN \(E_{\text{PEAK}} - E_{\text{ISO}}\) CORRELATION

Amati et al. (2002) showed that the rest frame \(E_{\text{peak}} - E_{\text{iso}}\) are correlated in 9 long GRBs detected by BeppoSAX. They found a correlation coefficient of 0.949 with a chance probability \(P = 5 \times 10^{-3}\). This correlation was confirmed by GGL04 using a large sample (objects listed in their Tab. 1 and 2) of 23 GRBs, with spectroscopically measured redshifts and published peak energy. Here, we update this sample with 4 more GRBs whose redshifts have been recently measured (see Ghirlanda et al. 2005).\(^3\) With these 27 bursts the Spearman rank correlation coefficient is \(r_s = 0.87\) and a chance probability \(P = 3.4 \times 10^{-9}\).

In Fig. 2 we show the rest frame \(E_{\text{peak}} - E_{\text{iso}}\) of these 27 GRBs (red symbols). The fit with a powerlaw model to these data points (weighting for the errors on both coordinates) is:

\[
\frac{E_{\text{iso}}}{E_{\text{peak}}} = 0.87^{+0.19}_{-0.13}\, > \, 0.52 \pm 0.06 \, \, 0.706 \pm 0.04 \, (4), (5), (6)
\]

\[\begin{array}{cccc}
\tau & 0.87^{+0.19}_{-0.13} & \ldots & \ldots \\
V & 0.3^{+0.11}_{0.07} & \ldots & \ldots \\
E_{\text{peak}} & 0.5 \pm 0.05 & 0.52 \pm 0.06 & 0.706 \pm 0.04 \\
\end{array}\]

Table 1. Slopes of the correlations between rest frame GRB quantities (for instance: \(\tau \propto L_{\text{iso},\text{peak}}^{0.87}\)). Ref: (1) Norris et al. 2000; (2) This work (Sec. 3) (3) Fenimore & Ramirez–Ruiz 2000, Reichart et al. 2001; (4) Yonetoku et al. 2004; (5) Amati et al. 2002; (6) Ghirlanda, Ghisellini & Lazzati 2004.

\[^2\text{http://coss.gsfc.nasa.gov/batse/BATSE_Ctlg/index.html}\]

\[^3\text{See also http://www.merate.mi.astro.it/~ghirla/deep/blink.htm}\]
with a $\chi^2 = 129.6/25$ dof. The distribution of the scatter measured along the fitting line (i.e. the distances of the data points to the fitting line) of the 27 GRBs is shown in Fig. 3 by the red-hatched histogram. Fitting with a Gaussian we find a dispersion $\sigma = 0.22$.

For the 442 GRBs with pseudo redshifts, we have estimated the errors on the rest frame $E_{iso}$ and $E_{\text{peak}}$ as follows. From $E_{\text{peak}} = E_{\text{peak,obs}}(1+z)$ we derive:

$$\left(\frac{\sigma_{E_{\text{peak}}}}{E_{\text{peak}}}\right)^2 = \left(\frac{\sigma_{E_{\text{peak,obs}}}}{E_{\text{peak,obs}}}\right)^2 + \left(\frac{\sigma_z}{1+z}\right)^2$$  \hspace{1cm} (2)

Similarly from $E_{iso} = 4\pi d_L^2 F/(1+z)$, where $d_L$ is the luminosity distance and $F$ is the GRB bolometric fluence, we obtain:

$$\left(\frac{\sigma_{E_{iso}}}{E_{iso}}\right)^2 = \left(\frac{2d_L \sigma_z}{d_L} - \frac{\sigma_z}{1+z}\right)^2 + \left(\frac{\sigma_F}{F}\right)^2$$  \hspace{1cm} (3)

where $d_L = \partial d_L/\partial z$.

BNB04 do not give the error on the estimated redshifts. However, it can be obtained from $L_{iso} = 4\pi d_L^2 \Phi$, where $\Phi$ is the peak flux, as follows:

$$\sigma_z^2 = \frac{d_L^2}{4d_L^4} \left[ \left(\frac{\sigma_{E_{iso}}}{E_{iso}}\right)^2 + \left(\frac{\sigma_\Phi}{\Phi}\right)^2 \right]$$  \hspace{1cm} (4)

The term $\sigma_{E_{iso}}/L_{iso}$ can be obtained from the lag–luminosity relation $L_{iso} = 10^B r_n^a$, using the error on the lag, i.e. $\sigma_T$ given by BNB04 in their table. However, also the error on the slope $n$ and on the normalization $B$ contribute to the error on the luminosity. Norris et al. (2000) and BNB04 do not give the uncertainty on these parameters. For this reason we recomputed the lag–luminosity relation (with the data of Table 1 of Norris 2000) in the “barycenter” of the data points, namely $r_n = 0.036$ s and $L_{iso,b} = 3.36 \times 10^{52}$ erg s$^{-1}$, in order to treat $B$ and $n$ as uncorrelated.

We found exactly the same slope and normalization but we could now also find the uncertainties on these quantities, i.e. $n \pm \sigma_n = 1.149 \pm 0.205$ and (in the coordinate system of the barycenter) the normalization is null but its error is nonzero i.e. $B \pm \sigma_B = 0.0 \pm 0.116$. We can finally compute the error:

$$\left(\frac{\sigma_{L_{iso}}}{L_{iso}}\right)^2 = 2 \ln 10 \left[ \left(\sigma_n \log \frac{\tau}{r_n}\right)^2 + \sigma_B^2 \right] + \left(\frac{n \sigma_T}{\tau}\right)$$  \hspace{1cm} (5)

Fig. 2 shows the 442 GRBs with pseudo redshifts (black symbols) \(^4\). Interestingly, we find that these 442 GRBs still show a highly significant correlation between the rest frame $E_{\text{peak}}$ and $E_{iso}$ with a Spearman correlation coefficient $r_s = 0.7$ and a chance probability $P = 2.1 \times 10^{-65}$. The partial correlation coefficient, i.e. removing the effect of $z$, is $r_p = 0.65$ and, therefore, indicates that the correlation is not determined by the common dependence of Eq. 2 and Eq. 3 on the term $(1+z)$. The fit (weighting errors on both coordinates) with a powerlaw to these data gives:

$$E_{\text{peak,100 keV}} = (4.34 \pm 0.05) \left(\frac{E_{iso}}{7.5 \times 10^{52} \text{erg}}\right)^{0.47 \pm 0.01}$$  \hspace{1cm} (6)

with a $\chi^2 = 1735/440$ dof. In this case the scatter distribution (filled histogram in Fig. 3) has a dispersion $\sigma = 0.22$, consistent with the dispersion of the 27 GRBs with spectroscopic redshifts. It is remarkable that both the slopes of the two correlations (Eq.

\(^4\) Note that $E_{iso}$ is computed accounting for the band k-correction as described in Eq.2 of GGL04.
1 and Eq. 2 above) and their scatter distributions are very similar. However, the two correlations have different normalizations: the 27 GRB with spectroscopic redshifts seem to define an envelope to the distribution of all GRBs of this sample. A possible reason for this behavior is that GRBs with spectroscopically measured redshifts tend to have fluences larger than the average, at least when comparing GRBs detected by BATSE or BeppoSAX. This fact has been pointed out also by NP04.

We finally consider the total sample of bursts, i.e. the 27 GRBs with spectroscopic redshifts plus the 442 GRBs here considered have a relatively large scatter in the $E_{\text{peak}} - E_{\text{iso}}$ plane. In GGL04 it has been shown that for the few GRBs with measured $\theta_{\text{jet}}$ this scatter reduces to only 0.1 dex on the Ghirlanda correlation. This suggests (see also Firmani et al. 2005) that the scatter might be due to the angle distribution of GRBs.

If we make the hypothesis that the Ghirlanda correlation has a scatter much smaller than the Amati correlation, we can derive the jet opening angle distribution for the 442 GRBs with pseudo redshifts. This is compared to the angle distribution of the few GRBs with measured jet break time and redshift (see Tab. 2 of GGL04) in Fig. 4. The angle distribution derived for the 442 GRBs and represented in Fig. 4 is described by a log-normal function:

$$N(\theta_{\text{jet}}) = \frac{1}{\sqrt{2\pi} \sigma \theta_{\text{jet}} a_1} \exp \left[ -\frac{(\ln \theta_{\text{jet}} - a_2)^2}{2a_1^2} \right]$$

(8)

The best fit parameters are $(a_1, a_2) = (2.2, 0.57)$ which lead to a peak value of $\sim 6.5^\circ$. Note that the derived distribution is the sum of the distribution of angles for bursts with any value of $E_{\text{peak}}$ and does not pretend to be representative of the distribution at each $E_{\text{peak}}$. Indeed, if the jet opening angle distribution remains the same for all values of $E_{\text{peak}}$, then we should expect the same slope for the Ghirlanda and Amati correlation. Since this is not the case, we can conclude that the current data indicate a trend: for smaller $E_{\text{peak}}$ and then $E_{\text{iso}}$, the average jet opening angle is larger than for larger values of $E_{\text{peak}}$ and $E_{\text{iso}}$. It is premature to conclude whether this trend is due to selection effects or if it has a physical origin (i.e. smaller jet opening angles for intrinsically more powerful bursts), and we plan to investigate in more detail this problem in a forthcoming paper.

5 COMPARISON WITH PREVIOUS WORKS

In the previous section we have shown that if the pseudo-redshifts obtained through the lag-luminosity relation are indicative of real redshifts, then the $E_{\text{peak}} - E_{\text{iso}}$ correlation exists even considering a large sample of GRBs. We now compare this conclusion with the conclusions of NP04 and BN05.

The method adopted by NP04 and BP05 starts from a given rest frame correlation $E_{\text{peak}} = K E_{\text{iso}}^{\eta}$, where the two quantities are related to the observables $E_{\text{peak}, \text{obs}} = E_{\text{peak}}/(1+z)$ and the fluence $F = E_{\text{iso}}/(1+z)/4\pi d_L^2(z)$. We can form the ratio,

$$\frac{E_{\text{peak}, \text{obs}}^{1/\eta}}{F} = K^{1/\eta} 10^{\sigma/\eta} 4\pi d_L^2(z) [(1+z)(1+\eta)/\eta]$$

(9)

where $\sigma$ corresponds to the scatter of data points around the correlation that is being tested. The RHS of the above relation is a function of $z$ and $\eta$ only, and is monotonically increasing with redshift if $\eta \geq 0.75$. For lower values of $\eta$ it has a maximum.

As in the case of NP04 and BP05, we take into account now the upper limit of the ratio $E_{\text{peak}, \text{obs}}^{1/\eta}/F$. This upper limit establishes an allowance region boundary on the corresponding plane. Furthermore, we include the scatter around the assumed correlation increasing the previous upper limit by the factor $10^{\sigma/\eta}$ (see Eq. 9).

NP04 and BP05 are testing the $E_{\text{peak}} - E_{\text{iso}}$ correlation as originally found with 9 bursts by Amati et al. 2001 , i.e. with slope $\eta = 0.5$. They allow for the possible scatter around this correlation with a factor 2 in the normalization of Eq. 9. This corresponds, for their assumptions, to consider $\sigma \sim 0.15$. As shown in this work (and see also GGL04) the 27 GRBs show a dispersion with $\sigma = 0.22$ in the $E_{\text{peak}} - E_{\text{iso}}$ plane around a correlation with slope $\eta = 0.56$ (see Eq.1). Moreover, we consider the $3\sigma$ consistency of our sample of bursts with this correlation.

For the above reasons we applied the same test adopted by NP04 and BP05, but using the correlation found here, with its proper scatter, i.e $\sigma = 0.22$. Note also that we use the peak energy of the time integrated spectrum $E_{\text{peak}}$.

In Fig. 5 we report the 27 GRBs with spectroscopic redshifts (open red circles, see. Sec. 3, plus 3 upper limits), as well as the 442

![Figure 4](Image)

Figure 4. Jet opening angle distribution for the sample of GRBs with pseudo redshift (blue hatched histogram). This has been obtained requiring they obey the Ghirlanda correlation. The solid black line is the log-normal fit to this distribution, which peaks at $\sim 6.5^\circ$. Also shown is the distribution (red hatched histogram) of measured jet opening angles for the 17 bursts in the sample of GGL04 of known redshifts and jet break time (Ghirlanda et al. 2005).
Figure 5. Observed plane. Fluence versus peak energy of the average spectrum for the sample of 546 GRBs selected in Sec. 2. Black dots are the 442 GRBs which has been used in Sec. 3. Grey stars are 104 GRBs excluded in the analysis of Sec. 3 either for their large redshifts or uncertain lags (see Sect. 2). Also shown are the 30 GRBs (open red circles) with known redshift (from GGL04, including/upper/lower limits on $E_{peak}$). The dashed red line (black solid line) represents the boundary defined by the correlation of Eq. 1 (Eq. 6). The hatched red region (yellow filled region) represents the boundary defined by the correlation of Eq. 1 (Eq. 6). The hatched red region (yellow filled region) represents the $3\sigma$ shift of the corresponding boundary due to the scatter. Points above these boundaries are fully consistent with the corresponding correlations. Upper/lower limits for data points are indicated by arrows. The dot–dashed black line represents the boundary of the Amati correlation adopted in BP05 and NP04.

GRBs (black dots) of the sample described in Sec. 2. The dashed red line (black solid line) represents the boundary defined by Eq. 1 (Eq. 6), while the red (yellow) hatched area shows the $3\sigma$ shift of the corresponding boundary related to the scatter. For a gaussian distribution the area below the $3\sigma$ limit is highly improbable for the elements of the corresponding sample. The point here is that 1.4% of the black dot distribution extends below the $3\sigma$ limit of Eq. 1 correlation (see Tab. 2 for the $1\sigma$ and $2\sigma$ fractions). This result makes Eq. 1 incompatible with the 442 BATSE GRB sample, in agreement with Nakar & Piran (2004) and Band & Preece (2005). This conclusion is strengthened by the fact that our allowance region is obtained using the upper limit of $E_{peak, obs}/F$.

We conclude that Eq. 1 has to be considered as a temporary estimate of the $E_{peak}-E_{iso}$ (Amati) correlation with an associated uncertainty likely due to the still small number of GRBs with known $z$. However, our main point is that the BATSE GRB sample confirms the existence of an $E_{peak}-E_{iso}$ correlation and the scatter of this correlation ($\sigma=0.22$) agrees with the scatter of the sample of the 27 GRBs with spectroscopic redshifts (Eq. 1).

6 CONCLUSIONS

Through a large sample of 442 BATSE GRBs, with known spectral peak energy (Y04) and pseudo redshift (BNB04), we have computed the rest frame peak energy $E_{peak}$ and the k-corrected equivalent isotropic energy $E_{iso}$. We have found that these two quantities are correlated: the power-law fit to this correlation gives a slope slightly flatter and an $E_{iso}$ a little smaller than the slope and the

|           | no scatter | $1\sigma$ | $2\sigma$ | $3\sigma$ |
|-----------|------------|-----------|-----------|-----------|
| Eq. 1 (red dashed) | 32%        | 68%       | 91.8%     | 98.6%     |
| Eq. 6 (black solid) | 59%        | 91.1%     | 98.7%     | 100%      |

Table 2. Consistency of the sample of 546 GRBs described in Sec. 2 with the Amati correlations as given by Eq. 1 and Eq. 6. The percentage represents the fraction of points above the lines in Fig. 5 (no scatter) or above the lower boundary of the corresponding $\sigma$ scatter.

$E_{iso}$ found with the 27 GRBs with spectroscopic redshifts, respectively. The scatter of the 442 data points around the fitting line is equal to the scatter of the 27 GRBs with known redshift, the existence of outliers being marginal.

We have further interpreted the scatter of these data points as due to the distribution of the jet opening angle of GRBs. By requiring that they obey the Ghirlanda correlation, we could estimate this distribution, which is a log-normal with an average angle of about 6.5°.

Our main conclusion is that the existence of an $E_{peak}-E_{iso}$ (Amati) correlation is confirmed, its scatter is probably rather well known, but its definitive estimate needs a wider sample of GRBs with spectroscopic measured redshifts.

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