The peak luminosity–peak energy correlation in gamma-ray bursts

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ABSTRACT
We derive the correlation between the peak luminosity \( L_{\text{iso}} \) and the peak energy of the \( \nu F_{\nu} \) spectrum \( E_{\text{peak}} \) using 25 long gamma-ray bursts (GRBs) with firm redshift measurements. We find that its slope is similar to that of the correlation between the time-integrated isotropic emitted energy \( E_{\text{iso}} \) and \( E_{\text{peak}} \). For the 16 GRBs in our sample with estimated jet opening angle, we compute the collimation-corrected peak luminosity \( L_{\gamma} \), and find that it correlates with \( E_{\text{peak}} \). This correlation has, however, a scatter larger than that of the correlation between \( E_{\text{peak}} \) and \( E_{\gamma} \) (the time-integrated emitted energy, corrected for collimation), which we ascribe to the fact that the opening angle is estimated through the global energetics. We have then selected a large sample of 442 GRBs with pseudo-redshifts, derived through the lag–luminosity relation, to test the existence of the \( L_{\text{iso}}-E_{\text{peak}} \) correlation. With this sample we also explore the possibility of a correlation between time-resolved quantities, namely \( L_{\text{iso}}^{p} \) and the peak energy at the peak of emission \( E_{\text{peak}}^{p} \).

Key words: cosmology: observations – gamma-rays: bursts.

1 INTRODUCTION
Several correlations have been identified among the intrinsic properties of the (small) population of gamma-ray bursts (GRBs) with measured redshifts \( z \). In particular, two spectral correlations have recently been discussed in the literature: (i) the ‘Amati correlation’ between \( E_{\text{peak}} \), the peak energy of the \( \nu F_{\nu} \) spectrum where most of the emission is radiated, and the total emitted energy (isotropic equivalent) \( E_{\text{iso}} \) (Amati et al. 2002, hereafter A02; Lloyd-Ronning & Ramírez-Ruiz 2002); and (ii) the ‘Ghirlanda correlation’ between \( E_{\text{peak}} \) and the collimation-corrected energy \( E_{\gamma} \) (Ghirlanda et al. 2004, hereafter GGL04). It is important to notice that these correlations refer to the time-integrated spectral properties of GRBs. This is true both for \( E_{\text{peak}} \) and for the spectral indices required to calculate the rest-frame bolometric \( E_{\text{iso}} \) and \( E_{\gamma} \).

However, time-resolved spectral analysis of large samples of bursts (e.g. Ford et al. 1995; Preece et al. 2000; Ghirlanda, Celotti & Ghisellini 2002) have proved that the GRB spectrum evolves in time during the prompt emission phase. The spectral evolution is different among different GRBs (e.g. Ford et al. 1995) and not clearly linked to other GRB global parameters (e.g. duration, number of peaks, peak flux). This spectral evolution may reveal the time variation of the parameters of the radiative process(es) acting in GRBs (e.g. Liang & Kargatis 1996) and/or of the relativistic properties of the emitting outflow (e.g. Ryde & Petrosian 2002). In order to understand the origin of such correlations, it is thus important to determine whether they are representing the characteristics of the global energetics or whether they hold for and are dominated by the time-resolved spectral properties, as expected if determined by the emission process(es). One obvious possibility is to test them against the peak luminosity, defined in a time interval of a few seconds centred around the GRB peak (e.g. Liang, Dai & Wu 2004).

This issue has been recently considered by Yonetoku et al. (2004, hereafter Y04). With a sample of 16 GRBs of known \( z \) they found that \( E_{\text{peak}} \propto L_{\gamma}^{0.5} \). This correlation appeared to be tighter (but with similar slope) than the \( E_{\text{peak}}-E_{\gamma} \) correlation, as originally found by A02. Note that the Y04 analysis adopts \( E_{\text{peak}} \) and the spectral indices of the time-integrated spectrum and not the spectral properties at the peak flux.

In this Letter we first re-examine the \( E_{\text{peak}}-L_{\gamma} \) correlation (i.e. the ‘Yonetoku correlation’) with an enlarged sample of 25 GRBs with spectroscopically measured \( z \) and published spectral properties. For 16 out of these 25 GRBs we have an estimate of their jet opening angle \( \theta_{j} \) (GGL04). We can thus calculate the collimation-corrected peak luminosity \( L_{\gamma} \) and verify if there exists the equivalent of the Ghirlanda correlation – namely \( L_{\gamma} \), replacing \( E_{\gamma} \) (Section 2). Then we consider a much larger sample of 442 GRBs with \( z \) estimated through the lag–luminosity correlation (Band, Norris & Bonnell 2004, hereafter BNB04) to test if the Yonetoku correlation still holds for this whole sample (Section 3). In Section 4, by means of this same sample, we also study the relation between \( L_{\gamma}^{p} \) and \( E_{\gamma}^{p} \) (i.e. using spectral parameters at the peak of the flux), to check whether this correlation is tighter than the Yonetoku one, and we discuss the
differences between the two. We find that the Ghirlanda correlation has a smaller scatter than the corresponding $E_{\text{peak}} - L_{\text{iso}}$ correlation. We give an interpretation of this result in Section 5 and draw our conclusions in the final Section 6. In this paper we adopt a standard Λ cold dark matter ($\Lambda$CDM) cosmology with $\Omega_{\Lambda} = 0.7$, $\Omega_{M} = 0.3$ and $h_0 = 0.7$.

2 THE $L_{\text{iso}} - E_{\text{peak}}$ CORRELATION

The bolometric gamma-ray luminosity can be defined once the prompt emission spectrum and the redshift $z$ of the source are known. GRB spectra are typically described by the Band function $N(\alpha, \beta, E_{\text{peak}})$ (Band et al. 1993), parameterized by low- and high-energy power laws (of photon indices $\alpha$ and $\beta$, respectively) and by peak energy $E_{\text{peak}}$ in the $vF_v$ representation.

The burst emission varies on short time-scales (e.g. Ramirez-Ruiz & Fenimore 1999) and no universal temporal profile describes the ‘zoology’ of burst light curves (e.g. Norris et al. 1996). However, in most cases, a dominating peak, with flux $F$ integrated in the observed energy band and over an observer-frame time-scale of ~1 s, can be identified in the prompt emission light curve. The rest-frame, bolometric (e.g. $1 - 10^4$ keV), isotropic peak luminosity, including the redshift-energy band correction, follows straightforwardly. In Table 1 we report the peak luminosities of the 32 GRBs examined by GGL04, computed assuming the time-integrated spectrum of each GRB (as from table 1 in GGL04).

![Table 1: Peak fluxes and bolometric luminosities for GRBs with measured $z$ (in GGL04). Also given are photon peak fluxes or energy peak fluxes with references (column 2: S = BeppoSAX, B = Batse, I = Inter-Planetary Network, IN = Integral, H = Hete-II) and corresponding observed energy band (column 5).](https://academic.oup.com/mnrasl/article-abstract/360/1/L45/960436)

References: (1) A02; (2) Y04; (3) 4th BATSE catalogue (Paciesas et al. 1999); (4) Frontera et al. (2001); (5) Price et al. (2002); (6) Piro et al. (2004); (7) Sakamoto et al. (2004); (8) Sazonov, Lutovinov & Sunyaev (2004); (9) Atteia et al. (2005); (10) Golenetskii et al. (2004).
The peak luminosity–peak energy correlation

**Figure 1.** Rest-frame peak energy $E_{\text{peak}} = E_{\text{peak}}(1 + z)$ versus bolometric peak luminosity. Samples: GRBs with measured $z$ listed in Table 1 (blue symbols) – upper/lower limits are excluded except for the two X-ray flashes (stars), shown for comparison with Fig. 1 of GGL04; 16 GRBs with known jet break time (from table 2 of GGL04) and hence jet opening angle $\theta_j$ (open orange circles); same 16 GRBs once corrected for the $(1 - \cos \theta_j)$ collimation factor (red filled circles). Fits: best power-law fit to the $E_{\text{peak}}-L_{\text{iso}}$ correlation (dashed blue line); best-fitting $E_{\text{peak}}-L_{\text{iso}}$ correlation (dashed red line); the Amati correlation from 27 GRBs in GGL04, GGF05 and Ghirlanda et al. (2005a) (long-dashed blue line); and the Ghirlanda correlation from GGL04 and Ghirlanda et al. (2005a) (dot–dashed blue line).

16 GRBs. The distribution of the scatter measured along the correlation (i.e. the distances of the data points from the fitting line) of the 25 GRBs is shown in Fig. 2 (red-hatched histogram). A Gaussian fit (red solid line) to the distribution yields a scatter comparable to that of the 27 GRBs in the $E_{\text{peak}}-L_{\text{iso}}$ plane (Ghirlanda et al. 2005b, hereafter GGF05; and black dashed line in Fig. 2; see also Ghirlanda et al. 2005a). For 16 out of the 25 GRBs listed in Table 1 we can correct their isotropic luminosity $L_{\text{iso}}$ for the jet opening angle $\theta_j$ (table 2 in GGL04), i.e. $L_{\gamma} = L_{\text{iso}}(1 - \cos \theta_j)$, with a corresponding error given by

$$
\left(\frac{\sigma_{L_{\gamma}}}{L_{\gamma}}\right)^2 = \left(\frac{\sigma_{L_{\text{iso}}}}{L_{\text{iso}}}\right)^2 + \left(\frac{\sigma_\theta \sin \theta_j}{1 - \cos \theta_j}\right)^2.
$$

(1)

The red symbols in Fig. 1 define the $L_{\gamma}$–$E_{\text{peak}}$ correlation. Again all the statistical parameters are reported in Table 2. The scatter of the best-fitting correlation (dashed red line in Fig. 1) decreases with respect to that using $L_{\text{iso}}$ – a trend similar to that found going from $E_{\text{iso}}$ to $E_{\gamma}$ (GGL04 and GGF05). As discussed by GGF05 in relation to the Amati correlation, also the scatter of the Yonetoku correlation found here can be interpreted as being due to the distribution of jet opening angles. Note, however, that the scatter in the $E_{\text{peak}}-L_{\gamma}$ correlation is larger than that of the Ghirlanda correlation $E_{\text{peak}}-E_{\gamma}$. This fact will be discussed in Section 5.

### 3 The Pseudo-Redshifts Sample

The original Amati correlation was found with nine BeppoSAX GRBs with known $z$. Through a redshift-independent method, Nakar & Piran (2004) and Band & Preece (2005) claimed that 40 and 88 per cent, respectively, of BATSE GRBs are inconsistent with the original Amati correlation. However, GGF05 (see also GGL04) have confirmed the above correlation (but finding a larger scatter) using a sample of 27 bursts with measured $z$ as well as using a sample of hundreds of GRBs with pseudo-$z$. An even more general conclusion, i.e. the consistency of the above correlations with the entire BATSE long-bursts sample, has been derived by Bosnjak et al. (2005).

The same test of GGF05 can be performed for the $E_{\text{peak}}-L_{\text{iso}}$ correlation found in Section 2. More importantly, it is worth investigating if its scatter and slope change using this much larger sample.

<table>
<thead>
<tr>
<th>Correlation</th>
<th>$N$</th>
<th>$r_s$</th>
<th>$P$</th>
<th>$r_c$</th>
<th>$A$</th>
<th>$S_0$</th>
<th>$\delta$</th>
<th>$\chi^2$/d.o.f.</th>
<th>$\mu$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{peak}}-L_{\text{iso}}$</td>
<td>25</td>
<td>0.83</td>
<td>2.4 $\times$ 10$^{-7}$</td>
<td>0.81</td>
<td>2.04 $\pm$ 0.05</td>
<td>7.5 $\times$ 10$^{51}$</td>
<td>0.50 $\pm$ 0.02</td>
<td>158/23</td>
<td>0.04</td>
<td>0.25</td>
</tr>
<tr>
<td>$E_{\text{peak}}-L_{\gamma}$</td>
<td>16</td>
<td>0.83</td>
<td>5.6 $\times$ 10$^{-5}$</td>
<td>0.84</td>
<td>2.23 $\pm$ 0.13</td>
<td>4.3 $\times$ 10$^{49}$</td>
<td>0.56 $\pm$ 0.03</td>
<td>50/14</td>
<td>$-$0.004</td>
<td>0.21</td>
</tr>
<tr>
<td>$E_{\text{peak}}-E_{\gamma}$</td>
<td>17</td>
<td>0.93</td>
<td>3.2 $\times$ 10$^{-8}$</td>
<td>0.92</td>
<td>2.52 $\pm$ 0.15</td>
<td>3.8 $\times$ 10$^{50}$</td>
<td>0.69 $\pm$ 0.04</td>
<td>20/15</td>
<td>0.01</td>
<td>0.11</td>
</tr>
<tr>
<td>$E_{\text{peak}}-E_{\gamma}$</td>
<td>442</td>
<td>0.71</td>
<td>1.6 $\times$ 10$^{-69}$</td>
<td>0.7</td>
<td>4.88 $\pm$ 0.06</td>
<td>1.9 $\times$ 10$^{52}$</td>
<td>0.48 $\pm$ 0.01</td>
<td>1595/440</td>
<td>$-$0.04</td>
<td>0.25</td>
</tr>
<tr>
<td>$E_{\text{peak}}-L_{\text{iso}}$</td>
<td>424</td>
<td>0.66</td>
<td>5.1 $\times$ 10$^{-65}$</td>
<td>0.65</td>
<td>3.37 $\pm$ 0.06</td>
<td>2.0 $\times$ 10$^{52}$</td>
<td>0.49 $\pm$ 0.01</td>
<td>1776/422</td>
<td>0.04</td>
<td>0.26</td>
</tr>
</tbody>
</table>
To this end, we consider the same sample as defined in GGF05, which comprises 442 GRBs with pseudo-$z$ (estimated by BNB04 through the lag–luminosity relation) and known peak energy of the time-integrated spectrum (found by Y04). Since the photon spectral indices are not given in Y04, in order to compute $L_{\text{iso}}$ we assume typical values, i.e. $\alpha = -0.8$, $\beta = -2.5$ (see e.g. Preece et al. 2000).

In Fig. 3 we show these 442 GRBs (black crosses) in the rest-frame $E_{\text{peak}}$ versus $L_{\text{iso}}$ plane, and in Fig. 2 we show the distribution of the scatter of the 442 points around this correlation (blue histogram in Fig. 2) together with its Gaussian fit (black solid line in Fig. 2). This scatter is only slightly larger than that defined by the 25 GRBs with measured $z$ (red-hatched histogram and red solid line in Fig. 2), and the slope of the correlations is similar (see Table 2).

For comparison with what was found for the Amati correlation by GGF05, Fig. 2 also reports the scatter distribution for the $E_{\text{peak}}-L_{\text{iso}}$ relation with the same samples of 27 and 442 GRBs (dot–dashed red and black dashed line, respectively). As already mentioned, the scatter of the Yonetoku correlation for the 442 GRBs can be interpreted as being due to the distribution of the jet opening angles. Assuming that the $E_{\text{peak}}-L_{\text{iso}}$ correlation has a smaller scatter than the Yonetoku one, we can estimate the jet opening angle distribution for the 442 GRBs: we find a lognormal with a peak at $\theta \sim 5^{\circ}$, i.e. consistent with that found by GGF05.

4 THE $E_{\text{peak}}^P-L_{\text{iso}}^P$ CORRELATION

With the aim of investigating the spectral correlations at the peak of the prompt emission, the most correct approach would be to analyse the spectrum of each GRB, time-resolved at the burst peak. This would allow the derivation of a peak spectral energy $E_{\text{peak}}^P$ and a luminosity (from the spectrum at the peak of the burst) $L_{\text{iso}}^P$ which, in general, might be different from the analogous integrated quantities.

Given that the GRBs listed in Table 1 were detected by different satellites and that the data are public only for BATSE, we can investigate the $E_{\text{peak}}^P-L_{\text{iso}}^P$ correlation only with the sample of 442 GRBs with pseudo-$z$. For these, in fact, Mallozzi et al. (1998) provide the spectral parameters of the peak spectrum, derived by integrating the GRB signal for $\sim 2$ s around the light curve peak, and BNB04 report the peak flux corresponding to the same peak spectrum. Note, however, that the peak luminosity is defined over a finite and constant observer-frame time interval around the GRB peak of $\sim 2$ s. For this reason the luminosities might be systematically underestimated for low-redshift GRBs. None the less, as shown in Fig. 5 (colour code), there is no apparent dependence of $L_{\text{iso}}^P$ on $z$, for those GRBs with spectroscopic $z$. This suggests that this systematic effect should not severely affect our results.

The sample of 442 GRBs allows a direct comparison with the results obtained in GGF05. However, we here exclude a few bursts either because their $E_{\text{peak}}^P$ is below the BATSE $\sim 30$-keV energy threshold (seven cases) or because $E_{\text{peak}}^P$ is not constrained by the spectral fit (11 cases with $\beta > -2$). We report in Fig. 4 the remaining 424 GRBs with pseudo-$z$. Also in this case we find a strong correlation with a scatter consistent with that obtained by adopting $L_{\text{iso}}^P$ (Section 3), and a slightly flatter slope. In other words, the peak energy and luminosity at the peak are correlated, but the correlation is not significantly tighter than the Yonetoku correlation (see Table 2).

5 THE ORIGIN OF THE SCATTER OF THE $E_{\text{peak}}-L_{\text{iso}}$ CORRELATION

In Section 2 we have derived the equivalent of the Ghirlanda correlation with the peak luminosity, i.e. $E_{\text{peak}}-L_{\text{iso}}$. This correlation (red symbols in Fig. 1) has a scatter a factor of $\sim 2$ larger than that of
the scatter distributions of the two quantities are correlated, but the scatter is instead similar to that proposed by Y04, although its scatter is much larger than they originally found with 16 GRBs. The scatter might be ascribed to the fact that the peak luminosity is less representative of the global energetics of the burst, which in turn is adopted to represent the total kinetic energy of the fireball and thus estimate the jet opening angle (e.g. Sari et al. 1999).

6 CONCLUSIONS

We have derived the \( \text{E}^\gamma \text{iso} - L^\gamma \text{iso} \) correlation with the current largest available sample of 25 GRBs with measured \( z \) and well-determined spectral properties (GGF04). This correlation has a slope of 0.5, i.e. similar to that proposed by Y04, although its scatter is much larger than they originally found with 16 GRBs. The scatter is instead comparable to what GGF05 found for the Amati correlation using the same sample of GRBs. Using the 442 GRBs with pseudo-\( z \), we still find a strong correlation, with similar scatter and slightly flatter slope than those found with the 25 GRBs of measured \( z \).

We then considered the robustness of correlations for quantities calculated at the peak of the emission, with respect to time-integrated properties. The former, in particular \( \text{E}^\gamma \text{peak} \) versus \( L^\gamma \text{iso} \) results in a correlation equally tight to that involving integrated quantities.

Correcting \( L^\gamma \text{iso} \) for collimation, we find that the corresponding \( \text{E}^\gamma \text{peak} - L^\gamma \text{iso} \) correlation has a slope flatter than the Ghirlanda correlation (0.57 versus 0.7) and a larger scatter (0.17 versus 0.1). The larger scatter might be ascribed to the fact that the peak luminosity is less representative of the global energetics of the burst, which in turn is adopted to represent the total kinetic energy of the fireball and thus estimate the jet opening angle (e.g. Sari et al. 1999).

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