Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 11 December 2007 (MN LATEX style file v2.2)

Energetics - Spectral correlations vs the BATSE Gamma-Ray Bursts population

Z. Bosnjak[1], A. Celotti[1], F. Longo[2], G. Barbiellini[2]
[1]*S.I.S.S.A., via Beirut 2-4, I-34014 Trieste, Italy*
[2]*Department of Physics and INFN, via Valerio 2, I-34100 Trieste, Italy*

ABSTRACT
Recently proposed correlations between the energetics of Gamma-Ray Bursts (GRB) and their spectral properties, namely the peak energy of their prompt emission, are found to account for the observed fluence distribution of all 'bright' BATSE GRB. Furthermore for an intrinsic GRB peak energy distribution extending toward lower energies with respect to that characterizing bright GRB, such correlations allow to reproduce the fluence distribution of the whole BATSE long GRB population. We discuss the constraints that such analysis imposes on the shape of the peak energy distribution, the opening angle distribution and the tightness of such correlations.

Key words: gamma–rays: bursts

1 INTRODUCTION

Among the most interesting clues on the physical processes taking place in GRB are the recently proposed correlations between their energetics and spectral properties. More precisely it has been suggested (Lloyd–Ronning, Petrosian & Mallozzi 2000; Amati et al. 2002 [A02 hereafter]; Sakamoto et al. 2004; Lamb et al. 2004; Atteia et al. 2004) that the apparent isotropic energy of the prompt correlates with the intrinsic peak energy (in $\nu f(\nu)$) of the integrated emission, with a dependence $E_{\rm iso} \propto E_{\rm peak}^{0.5}$. A similar correlation has been found between $E_{\rm peak}$ and the peak luminosity (Yonetoku et al. 2004). More recently, Ghirlanda, Ghisellini & Lazzati (2004) (GGL04 hereafter), by correcting for the putative fireball opening angle estimated from the (achromatic) break time in the afterglow light curve (Sari, Piran & Halpern 1999; Frail et al. 2001; Bloom, Frail & Kulkarni 2003) argued that an even tighter correlation holds between the actual energetic and $E_{\rm peak}$, namely $E_\gamma \propto E_{\rm peak}^{0.7}$. Such correlations are based on (at most) the ~ 40 long GRB for which redshift information is currently available. Although no unique and robust interpretation of such results has been found so far (e.g. Schaefer 2003; Liang, Dai & Wu 2004; Eichler & Levinson 2004; Rees & Meszaros 2005), it is clear that if these were to hold for the whole GRB population (see Friedman & Bloom 2004; Nakar & Piran 2004; Band & Preece 2005 for dissenting views), they could be powerful clues to the physical origin of the prompt emission and have important repercussions on the cosmological use of GRB.

In order to test whether these relations characterize the bulk of the GRB population (until a significantly larger number of redshift can be determined), we tested their consistence against the observed peak energy and fluence distributions, under the assumption that the GRB events follow the cosmological star formation rate redshift distribution. Although the found statistical consistency is not a proof of such correlations, it supports the view that they are indeed representing an intrinsic properties of all (BATSE) long GRB.

The outline of this Letter is the following: we detail our assumptions and procedure in Section 2, present our results in Section 3 and finally discuss them in Section 4. Preliminary results of this work have been presented by Bosnjak et al. (2004). While finishing writing this Letter we received the manuscript from Ghirlanda, Ghisellini & Firmani (2005), who – through a complementary and independent analysis – reach remarkably similar results to those reported in this work.

2 METHOD AND ASSUMPTIONS

We aim at testing whether the observed peak energy and fluence distributions are consistent with the A02 and GGL04 proposed correlations.

More precisely, we considered the sample of BATSE GRB analyzed by Preece et al. (2000) (referred to as the 'bright' BATSE sample hereafter), consisting of 156 events for which $E_{\rm peak}$ have been estimated. We then simulated – via Monte Carlo method – the fluence distribution for a population of GRB characterized by the corresponding $E_{\rm peak}$ distribution as follows:

– assumed that the GRB population follows the star formation rate distribution in redshift (as estimated by Madau & Pozzetti 2000), namely $R_{\rm GRB}(z) = 0.3\exp(3.4z)[\exp(3.8z)+45]^{-1}$ M$_\odot$ yr^{-1} Mpc^{-3};

– adopted the observed bright BATSE GRB $E_{\rm peak}$ distribution, as obtained by averaging the Preece et al. (2000) results of their time resolved spectral analysis;

–randomly assigned a redshift and a characteristic $E_{\rm peak}$ to each event;

–adopted the A02 correlation (and its spread) to estimate the corresponding energetics;

–by applying the cosmological corrections[1] estimated the corresponding fluence in the 50-300 keV energy range (a typical Band spectral representation with $\alpha = -1$ and $\beta = -2.25$ has been adopted, see Preece et al. 2000);

–compared the resulting fluence distribution with that of bright BATSE GRB. The comparison of fluences clearly avoids the need of a further assumption about the GRB durations.

An analogous test by adopting the GGL04 relation is clearly less straightforward, as it requires the information on the GRB opening angle distribution. The latter is however constrained only by 16 (8) GRB for which an estimate (limit) on the opening angle can been determined from the break time of the afterglow light curve (see GGL04). We approximated such distribution as a lognormal function and constrained it by requiring that it can reproduce the observed fluences.

We then explored the possibility that the whole of the BATSE long GRB population might follow such relations. Clearly, if indeed these were to hold, the adoption of the BATSE bright GRB peak energy distribution biases the selection to typically high fluence events. In order to account also for dim GRB we thus extrapolated the $E_{\rm peak}$ distribution toward lower energies.

The comparison between the simulated and observed fluences has been performed by estimating the maximum difference D in the cumulative distributions, as in the Kolmogorov-Smirnoff (KS) test. The parameter D has been used to compare the agreement with data of the different models (i.e. different assumptions/parameters), although formally the associated probability of two distributions being drawn from the same parent one would be only $P_{\rm KS}$= 0.002 for $D < 0.07$ (which we treat as a limit for a qualitatively satisfactory agreement).

3 RESULTS

The strongest finding is indeed that the simple adoption of the A02 correlation generates a fluence distribution consistent with the observed one for bright BATSE GRB. The comparison of the predicted and observed distributions is shown in Figure 1 (top panel) and their formal consistency is confirmed by a KS test (probability $P_{\rm KS}$= 0.06).

The observed fluences can be satisfactorily reproduced ($P_{\rm KS}$= 0.18) also by adopting the GGL04 relation for an lognormal opening angle distribution peaking around $\sim 4-5^o$ and mimicking the distribution of the (few) estimated opening angles (see Figure 2).

In order to account for the fluences of the whole BATSE GRB population [2] (~ 1500 events), the intrinsic peak energy distribution has to extend to lower energies, as the spread in fluences arising from the cosmological distance of GRB would span a range much smaller than what required. Furthermore, as the range in $E_{\rm peak}$ would dominate in determining the range in fluences, the shape of the $E_{\rm peak}$ distribution should be qualitatively similar to that of fluences.

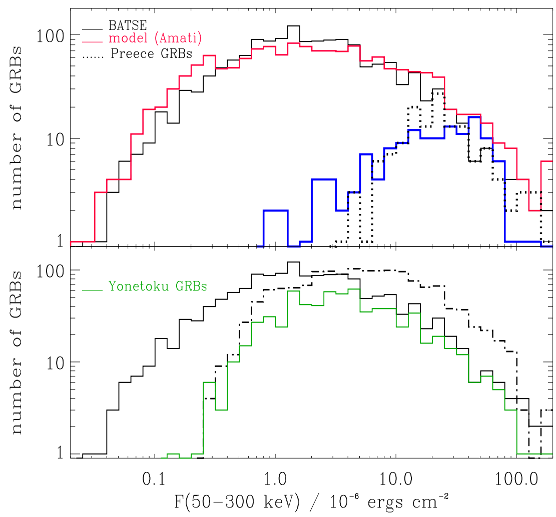

Figure 1. Fluence distributions for ‘bright’ BATSE GRB (Preece et al. 2000) (black dotted line), the whole of BATSE long GRB population assuming: the A02 relation (top panel, blue and red lines); the GGL04 relation, assuming the ‘bright’ GRB opening angle distribution for the whole of the BATSE sample (black dot-dashed line, bottom panel); the observed distribution of the sample by Yonetoku et al. (2004) (green line, bottom panel).

Indeed, in Figure 3 we report the $E_{\rm peak}$ distribution which allows to satisfactorily reproduce the overall fluence distribution (as shown in Figure 1, top panel) which broadly peaks around ~ 80 keV. Attempts have been made to determine how such extrapolation is constrained, by considering also other $E_{\rm peak}$ distributions (shown in Figure 3), namely a distribution increasing further and peaking around ~ 60 keV and one peaking around $100-200$ keV, the latter reproducing the distribution for the GRB examined by Yonetoku et al. (2004). Interestingly our analysis is quite sensitive to the extrapolation, resulting in inconsistent fluence distributions for either alternatives (by over and under estimating the dimmest GRB, respectively (the result for the latter case is shown in Figure 1, bottom panel).

However when the GGL04 correlation is adopted, the extrapolation to lower $E_{\rm peak}$ shown in Figure 3 cannot account by itself for the fluence distribution if the (narrow) distribution of angles inferred for bright GRB is adopted. Indeed, as shown in Figure 1 (bottom panel), the corresponding fluence distribution in such case results to be a factor ~ 5 higher and narrower than the observed one. Within this scenario such discrepancy can be accounted for if BATSE GRB include a large fraction of bursts with wider opening angles: Figure 2 reports the inferred (lognormal) opening angle distribution which yields a satisfactory agreement for the fluences. This peaks around 6-8^o and extends to about 20-25^o. The larger central value of the angles has to be considered as a representative parameter, which could in principle mimic other effects, like possible absorption.

It should be stressed that both the extrapolated $E_{\rm peak}$ as well as the opening angle distributions are quite constrained, both in shape and in extent.

[1] Throughout this work we adopt a ‘concordance’ cosmology Ω_Λ = 0.7, $\Omega_{\rm M}$ = 0.3, and H_0 = 65 km s^{-1} Mpc^{-1} (H_0 = 70 km s^{-1} Mpc^{-1} for the GGL04 case).
[2] http://cossc.gsfc.nasa.gov/batse/BATSE_Ctlg/flux.html

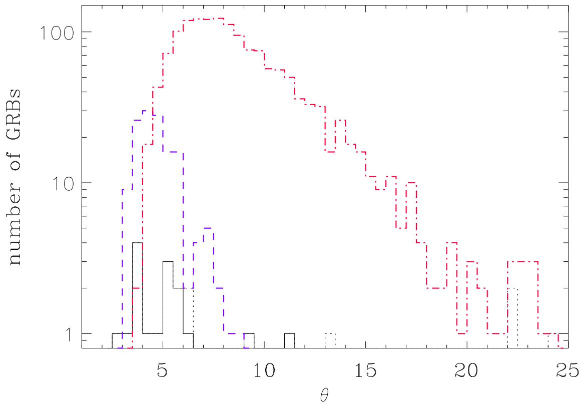

Figure 2. Opening angle distributions, as constrained by the request that the GGL04 correlation is representative of bright BATSE GRB (dashed line) and the whole of the BATSE GRB population (dot-dashed). Reported are also the values inferred from the break time of the afterglow light curves (solid histogram, data from GGL04).

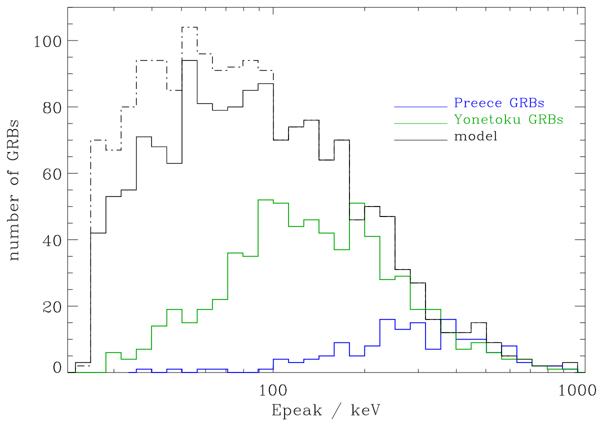

Figure 3. $E_{\rm peak}$ distributions for the bright BATSE GRB (observed, Preece et al. 2000), for the GRB sample examined by Yonetoku et al. (2004) and that adopted in this work for the whole BATSE long GRB sample. The dashed line shows the other $E_{\rm peak}$ distribution tested.

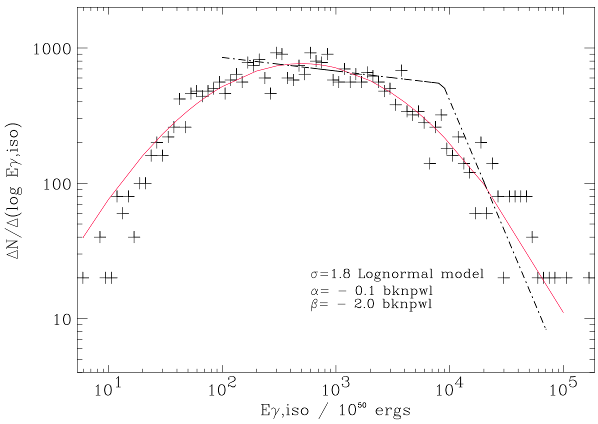

Figure 4. 'Luminosity' (E_γ) function of BATSE GRB simulated in this work. Also reported the lognormal fit to the simulated distribution and the slopes inferred by Guetta et al. (2004) for a broken power-law representation of the luminosity function.

3.1 Inferred properties of BATSE GRB

Within the above assumptions, the population of GRB with properties consistent with those of BATSE GRB can be characterized in terms of redshift distribution and luminosity function.

Given that the redshift (up to $z \sim 5$) is not the primary driver for the observed low fluence events, the sample basically follows the assumed cosmological distribution. For this same reason, the analysis did not give significantly different results (within a factor 2 in fluences) when a star formation rate $\sim$ constant above $z \sim 2$ (case 2 in Porciani & Madau 2001) was adopted.

The inferred 'luminosity' function (in terms of E_γ), reported in Figure 4, clearly reflects the $E_{\rm peak}$ distribution. Interestingly, this well agrees with those deduced from number counts constraints, providing a self-consistency check on the assumptions imposed in the present analysis. In fact, the parameters which characterize it (as lognormal function) are consistent with those determined by Sethi & Bhargavi (2001) and Schmidt (2001) in terms of peak and width (including a decline at low E_γ) for an average GRB duration of $\sim$ 100 sec, and qualitatively consistent with the characterization reported by Guetta, Piran & Waxman (2004) for the higher energy part in terms of a broken power–law (see Figure 4).

3.2 Spread of the distributions

While the above results do support the existence of a connection between energetics and $E_{\rm peak}$, it is of great relevance both for understanding the robustness of the physical process behind these correlations as well as the possible use of GRB for cosmological studies, to quantitatively determine any intrinsic spread of such relations.

Indeed Nakar & Piran (2004) have recently argued that such relations might be the result of selection effects, as a large number of GRB (at least 50 per cent of their sample) do not appear to follow the A02 correlation. Similar findings have been reported by Band & Preece (2005) from a more refined analysis, who conclude that 88 per cent of BATSE bursts are inconsistent with the A02 relation, and only at most 18 per cent qcould follow it.

Whether these results imply that the correlations are totally spurious - contrary to our indications - or are significantly broader than estimated so far, has indeed to be determined.

To this aim, we simply allowed for a variable spread (σ), approximated as a Gaussian in logarithmic energy, around the A02 correlation. The comparison of the simulated fluence distributions with the BATSE ones constrains such Gaussian spread to be centered at $E_0 \simeq E_{\rm A02}$ ($\log(E_0/E_{\rm A02}) = 0.05$ for the bright GRB subsample) and $\sigma = 0.17$, the latter fully compatible with the actual spread in the A02 correlation (see GGL04). While smaller σ are acceptable, a very strong upper limit $\sigma < 0.3$ is imposed by the data: such large spread implies an excess of GRB both at high and low fluences, arguing against the possibility that the A02 correlation is in fact just a limit (see Nakar & Piran 2004; Band & Preece 2005).

4 DISCUSSION AND CONCLUSIONS

The main result of this work is that the simple assumptions that there is a link between the energetics and the typical energy of emit-

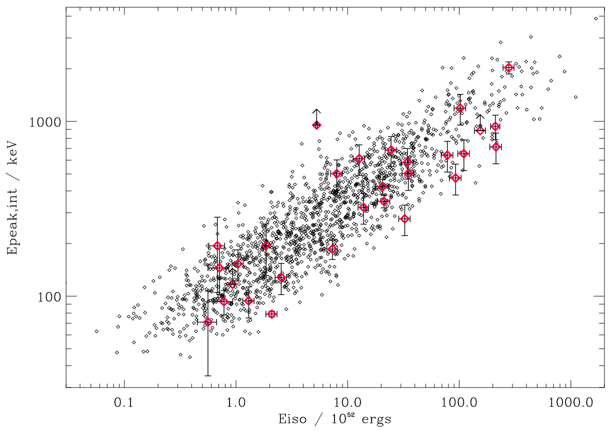

Figure 5. Distribution of the simulated GRB in the $E_{\rm peak}$ vs $E_{\rm iso}$ plane, including the spread around the A02 correlation. The larger symbols indicate the GRB considered by GGL04.

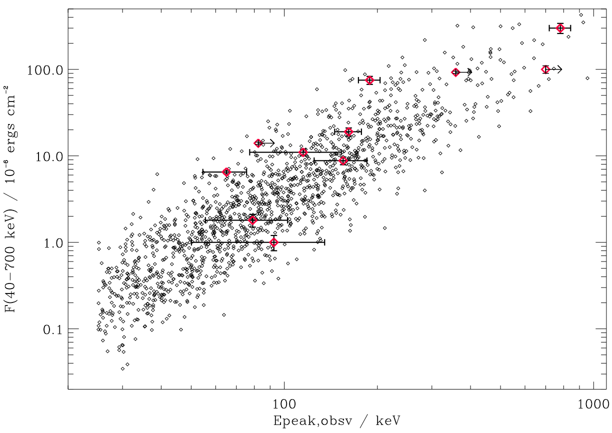

Figure 6. Fluence vs $E_{\rm peak}$ distributions as inferred from the model. The diamonds (larger symbols) indicate the GRB events considered by GGL04 (for the same energy band), and the black symbols the GRB reported by Yonetoku et al. (2004).

ted photons in the prompt phase, as described by the correlations proposed by A02 and GGL04, and that GRB follow the star formation rate redshift distribution, are fully consistent with the properties of the 'bright' BATSE GRB (sample by Preece et al. 2000). For a peak energy distribution extending to lower frequencies, such a consistency is found also for the whole of the BATSE population (long GRB). The $E_{\rm peak}$ distribution, extending to the range of definition of X-ray rich bursts and X-ray flashes, corresponds to a rising number of events at lower $E_{\rm peak}$ with respect to that of bright GRB, flattening and declining below $\sim$ 80 keV. The extrapolation down to $E_{\rm peak} \sim 200$ keV is fully consistent with that sampled by the GRB analyzed by Yonetoku et al. (2004) at fluences lower that those of the Preece et al. (2000) GRB.

By adopting an opening angle (lognormal) distribution peaking around $4-5^o$ and extending to $\sim 8^o$, roughly similar to that observed (for only ~ 15 GRB), consistency with the bright GRB sample is found also adopting the GGL04 relation. An agreement with the whole BATSE sample does instead require an opening angle distribution broader and extending to larger angles (peaking around $\sim 6-8^o$ and up to $\sim 25^o$). Such indication reflects the fact that the A02 and GGL04 distributions have a different slopes, i.e. the suggestion of a connection between the GRB opening angle and energetics E_γ (and/or $E_{\rm peak}$). However, our analysis does not allow to definitely exclude an A02 correlation with slope similar to the GGL04 one, i.e. an opening angle distribution independent of energy.

This study indicates that the distribution of fluences of dim GRB cannot be ascribed to the cosmological distribution of GRB but is dominated by a spread in $E_{\rm peak}$, and is thus rather insensitive to the actual GRB redshift distribution at high z.

While these findings of consistency cannot prove the reality of an intrinsic tight link between the energetics and spectra of GRB, they significantly corroborate such possibility. The tested scenario appears fully consistent. The spread in the above correlations provide an indication of the strength of the physical connection between the energetics and spectral properties of the prompt emission, and a constraint on the statistics required to use GRB as cosmological distance indicators.

It should be stressed that the above constraints refer only to GRB observable and observed by the fluence and energy range sensitivity of BATSE. Selection effects even within the BATSE sample (related to the determination of redshift and opening angle) have being indeed claimed to be responsible for the A02 (and GGL04) correlations by Nakar & Piran (2004) and Band & Preece (2005), on the basis of events not consistent with them [3]. Two well known 'outliers' of such correlations are provided by two of the GRB with evidence of an associated Supernova (see also Bosnjak et al. 2005 for more cases), as well as short GRB (Ghirlanda, Ghisellini & Celotti 2004). Nakar & Piran (2004) and Band & Preece (2005) argue that actually a large fraction of the whole GRB population does indeed violate the above relations.

We cannot identify the reason of such discrepancy in the results. Clearly, it is possible that the agreement we find with the BATSE fluence distributions is by chance. Alternatively, one could ascribe it to a significant spread in the above correlations. However an estimate of the distribution of the parameter '$d_{\rm k}$' (i.e. the distance from the A02 correlation, as defined by Nakar & Piran 2004) shows that our simulated sample is inconsistent with their findings within the spread 'allowed' by our analysis: the distribution we find comprises proportionally more GRB with low '$d_{\rm k}$'. In Figure 5 we report the simulated GRB in the $E_{\rm peak}$ vs $E_{\rm iso}$ plane, together with the GRB considered by GGL04 and in Figure 6 the analogous information in the fluence vs $E_{\rm peak}$ plane.

One aspect worth mentioning, regarding the possibility that the 'outliers' found by the above authors might represent the tail of a distribution, is the large fraction of high $E_{\rm peak}$ GRB found by Nakar & Piran (2004), who estimated $E_{\rm peak} > 250$ keV for about 50 per cent of their GRB (i.e. corresponding to about 25 per cent of the whole BASTE long GRB sample). This fraction is not reproduced in the sample by Yonetoku et al. (2004) whose lower fluence GRB are typically characterized by softer spectra, supporting our findings. We stress that our analysis does not suffer from the fluence (and z) limitations required for the estimate of $E_{\rm peak}$. Unfortunately, the lack of detailed information on the GRB considered in those two studies does not allow a deeper investigation on the found discrepancy at this stage.

The direct testing of such correlations based on individual

[3] Although it might be difficult to pinpoint a reason why the GGL04 correlation might be tighter than the A02 one.

events requires the determination of redshift (and break time in the afterglow light curves) for a significant number of GRB. Indirect support can however come from the comparison of the inferred $E_{\rm peak}$ distribution with the extension towards lower energy, to X–ray rich GRB and X–ray flashes, as will be provided by HETE 2 and Swift.

ACKNOWLEDGMENTS

We thank Giancarlo Ghirlanda, Gabriele Ghisellini and Claudio Firmani for showing us the results of their work before submitting their paper. The Italian MIUR and INAF (ZB and AC) are acknowledged for financial support.

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