

## Intrinsic spectra and energetics of cosmological Gamma-Ray Bursts

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**Abstract** We extend a previous work on the intrinsic spectral properties and energetics of GRBs with known redshift based on 12 BeppoSAX events by including in the sample a total of 10 more events detected either by BATSE, BeppoSAX or HETE-2. An indication of a trend of the total isotropic equivalent radiated energy,  $E_{\text{rad}}$ , with redshift is found and, remarkably, the previously found relationship between the peak energy of the rest-frame  $\nu F\nu$  spectrum,  $E_{\text{p}}^{\text{rest}}$  and  $E_{\text{rad}}$  is confirmed and its significance increased. The implications of these results are briefly discussed in the framework of standard models for the prompt emission of GRBs.

**Key words:** gamma-rays: observations – gamma-rays: bursts

### 1 INTRODUCTION

In the past, the spectral studies of GRBs put in evidence very important properties, like fast spectral evolution, non thermal spectrum with a smoothly broken power-law shape that can be satisfactorily reproduced in many cases by Synchrotron Shock Models (SSM), narrow distributions of the spectral parameters, in particular of the peak energy  $E_{\text{p}}$  of the  $\nu F\nu$  spectrum, hardness-duration and hardness-intensity relationships (e.g. Band et al. 1993, Tavani 1997, Paciesas et al. 1999, Preece et al. 2000, Frontera et al. 2000). Nevertheless, the impact of these results on the understanding of the nature of GRBs and of the emission mechanism(s) producing the prompt emission were strongly limited by the lack of knowledge of the GRBs distance scale and thus of their energetics and intrinsic spectral shape. But in 1997, the BeppoSAX breakthrough discovery of afterglow emission from GRBs, leading to the first redshift measurements for these sources, started a new era in GRB science. All the GRBs for which a redshift could be estimated lie at cosmological distances ( $z = 0.17 - 4.5$ ) (except for GRB 980425 if associated with SN 1998bw,  $z=0.0085$ ) and the total isotropic equivalent radiated energy,  $E_{\text{rad}}$ , is huge: from  $\sim 10^{51}$  erg up to  $\sim 10^{54}$  erg (again with the exception of GRB 980425). The spectral analysis of GRBs with known redshift ( $\sim 30$  events up to now) can produce a big step forward with respect to previous spectral studies, allowing e.g. the measurement of the distribution of the rest-frame peak energy,  $E_{\text{p}}^{\text{rest}}$ , the study of spectral parameters as a function of  $E_{\text{rad}}$  and redshift, the search for redshift indicators.

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In a previous work (Amati et al. 2002), we studied the intrinsic spectra and energetics of a sample of 12 GRBs simultaneously detected by the WFC (2–28 keV) and GRBM (40–700 keV) instruments on board BeppoSAX (Boella et al. 1997) and for which redshift estimates were available. This analysis took advantage also of the extension of the spectral fitting energy range down to 2 keV, allowing better estimate of low energy index  $\alpha$  with respect e.g. to BATSE (20–2000 keV) and to reduce the  $\alpha$ – $E_p$  correlation and data truncation effects. The main results were the indications of a trend of  $E_{\text{rad}}$  and  $\alpha$  with  $z$  and, importantly, the evidence of a correlation between  $E_p^{\text{rest}}$  and  $E_{\text{rad}}$ . The latter correlation is in agreement with previous indications inferred from BATSE detected events without knowledge of  $z$  (Lloyd, Petrosian & Malozzi 2000) and with the predictions of some realizations of SSM scenarios. In addition, our results indicated that the intrinsic distribution of  $E_p^{\text{rest}}$  could be much broader than that inferred from non redshift–corrected spectra. A detailed analysis of the combined WFC/GRBM sensitivity thresholds showed that selection and data truncation effects did not affect significantly our results.

The major problem with these results was the small number of events included in the sample, but now spectral parameters are available for more GRBs with known redshift (e.g. Jimenez, Band & Piran 2001, Barraud et al. 2003). In this work we present and discuss the results of the same analysis on an enlarged sample including, in addition to the 12 events considered in Amati et al. (2002), 4 HETE–2 events, 4 BATSE events and 2 more BeppoSAX events, for a total of 22 events (Table 1).

**Table 1** Redshift, intrinsic spectral parameters and energetics of the GRBs included in our sample. See text for details and references.

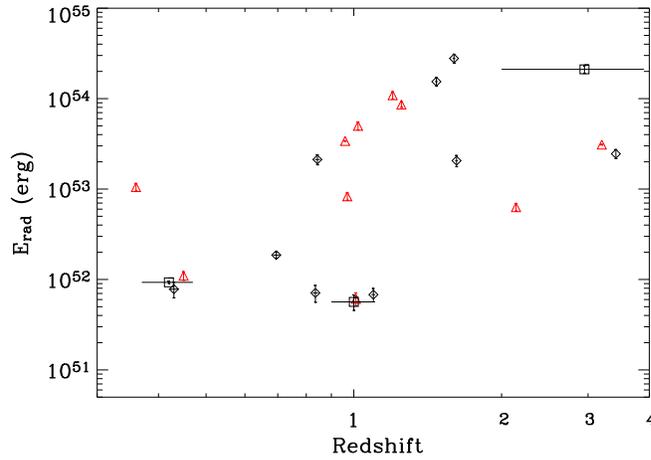
GRB	Mission	$z$	Model	$\alpha$	$E_p^{\text{rest}}$ (keV)	$E_{\text{rad}}$ ( $10^{52}$ erg)
970228	SAX	0.695	Band	$-1.54 \pm 0.08$	$195 \pm 64$	$1.86 \pm 0.14$
970508	SAX	0.835	Band	$-1.71 \pm 0.10$	$145 \pm 43$	$0.71 \pm 0.15$
970828	BATSE	0.958	Band	$-0.70 \pm 0.14$	$586 \pm 117$	$34 \pm 4$
971214	SAX	3.412	Band	$-0.76 \pm 0.17$	$685 \pm 133$	$24 \pm 3$
980326	SAX	0.9–1.1	Band	$-1.23 \pm 0.21$	$71 \pm 36$	$0.56 \pm 0.11$
980329	SAX	2.0–3.9	Band	$-0.64 \pm 0.14$	$935 \pm 150$	$211 \pm 20$
980613	SAX	1.096	Band	$-1.43 \pm 0.24$	$194 \pm 89$	$0.68 \pm 0.11$
980703	BATSE	0.966	Band	$-1.31 \pm 0.26$	$503 \pm 64$	$8.3 \pm 0.8$
990123	SAX	1.600	Band	$-0.89 \pm 0.08$	$2030 \pm 161$	$278 \pm 32$
990506	BATSE	1.307	Band	$-1.37 \pm 0.28$	$624 \pm 130$	$109 \pm 11$
990510	SAX	1.619	Band	$-1.23 \pm 0.05$	$423 \pm 42$	$20 \pm 3$
990705	SAX	0.842	Band	$-1.05 \pm 0.21$	$348 \pm 28$	$21 \pm 3$
990712	SAX	0.433	Band	$-1.88 \pm 0.07$	$93 \pm 15$	$0.78 \pm 0.15$
991216	BATSE	1.02	Band	$-1.23 \pm 0.25$	$645 \pm 130$	$50 \pm 5$
000214	SAX	0.37–0.47	CPL	$-1.62 \pm 0.13$	$>117$	$0.93 \pm 0.03$
010222	SAX	1.477	Band	$-1.35 \pm 0.19$	$>886$	$154 \pm 17$
010921	HETE–2	0.451	CPL	$-1.49 \pm 0.05$	$152 \pm 37$	$1.10 \pm 0.11$
011121	SAX	0.362	Band	$-1.42 \pm 0.14$	$295 \pm 35$	$11 \pm 1$
011211	SAX	2.140	Band	$-0.84 \pm 0.09$	$186 \pm 24$	$6.3 \pm 0.7$
020124	HETE–2	3.2	CPL	$-1.10 \pm 0.08$	$504 \pm 95$	$31 \pm 0.3$
020813	HETE–2	1.254	CPL	$-1.05 \pm 0.02$	$477 \pm 22$	$86 \pm 9$
021211	HETE–2	1.01	Band	$-0.90 \pm 0.18$	$116 \pm 24$	$0.61 \pm 0.12$

## 2 GRB SAMPLE AND DATA ANALYSIS

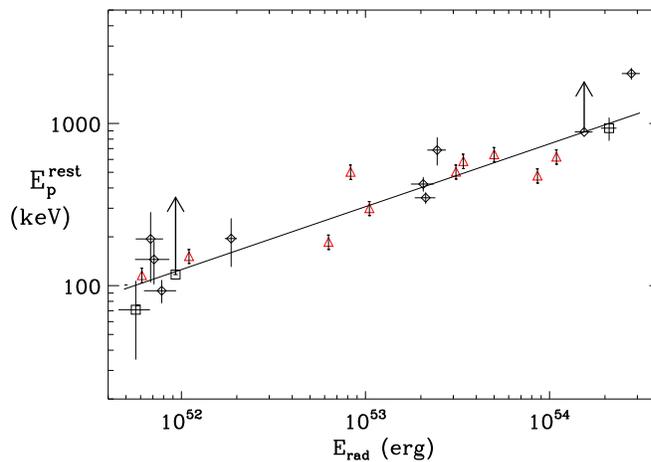
The GRBs included in our sample and their redshift values, see Jimenez, Band & Piran (2001), Amati et al. (2002), Bloom (2003), Atteia (2003) for a complete list of references, are reported in Table 1, together with the most relevant best fitting parameters of their intrinsic spectra and the computed isotropic equivalent radiated energies. The fitting model was either the canonical Band function (Band et al. 1993), whose spectral parameters are the low energy index  $\alpha$ , the high energy index  $\beta$  and the break energy  $E_0$ , or, for three of the HETE-2 events (see Barraud et al. 2003), a cut-off power-law with index  $\alpha$  and cut-off energy  $E_c$ . The spectral shape of these two models is nearly the same up to energies not much higher than  $E_p^{\text{rest}}$ , which is given by  $(2 + \alpha)$  multiplied by  $E_0$  or  $E_c$ . For the BeppoSAX events, the fits were performed on the blue-shifted spectra in order to obtain the spectral shape in the GRB cosmological rest-frame, as was done in Amati et al. (2002). For the HETE-2 and BATSE events we derived the parameters of the cosmological rest-frame spectra from the published measured ones by accounting for the fact that  $\alpha$  and  $\beta$  are invariant with redshift,  $E_0$  scales as  $(1 + z)$  and the overall normalization as  $(1 + z)^{\alpha+1}$ . The measured spectral parameters of the the BATSE events were taken from Jimenez, Band & Piran (2001) and those of the HETE-2 events were taken from Barraud et al. (2003) and Atteia (2003). The uncertainties on the parameters values reported in Table 1 are at  $1\sigma$  level and, when not available, are conservatively assumed to be 20% of the best fit values. The total radiated energies were then computed by integrating the best fit models to the cosmological rest-frame spectra from 1 to 10000 keV and scaling by the luminosity distances in the way described by Amati et al. (2002). We assumed a standard cosmology with  $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_m = 0.3$  and  $\Omega_\Lambda = 0.7$ . The uncertainties on the  $E_{\text{rad}}$  values reported in Table 1 were derived from those on the measured fluences, which were assumed to be 10% when not available. The Pearson's correlation coefficients  $r$  reported and discussed in the next section were performed by properly weighting for data uncertainties.

## 3 RESULTS

The spectral parameters in the cosmological rest frame and the isotropic equivalent total radiated energies of the GRBs included in our sample, computed as described in the previous section, are reported in Table 1. The values of  $E_{\text{rad}}$  span over nearly three orders of magnitude and a considerable spread of the intrinsic  $E_p^{\text{rest}}$  values is found. The values of  $\alpha$  also vary substantially from burst to burst and are always consistent with the limits predicted for optically thin synchrotron emission ( $-0.67, -1.5$ ). As can be inferred directly from Table 1, the indication of a dependence of  $\alpha$  on  $z$  is slightly weakened with respect to what found for the 'old' sample. In Fig. 1 and Fig. 2 we plot  $E_{\text{rad}}$  vs.  $z$  and  $E_p^{\text{rest}}$  vs.  $E_{\text{rad}}$ , respectively. By adding the new 10 events (triangles), the trend of  $E_{\text{rad}}$  with  $z$  is still confirmed; in particular there is indication of a trend of the maximum isotropic equivalent radiated energy with redshift, with the only exception of GRB 011121. The correlation coefficient between the logarithms of these two quantities is  $r=0.61$  for 22 events, corresponding to a chance probability of  $\sim 0.2\%$ . But, as apparent from Fig. 2, the most striking result is that with the addition of the new events the correlation between  $E_p^{\text{rest}}$  and  $E_{\text{rad}}$  is confirmed and its significance increased. Indeed, the correlation coefficient between  $\log(E_p^{\text{rest}})$  and  $\log(E_{\text{rad}})$  is  $r = 0.90$ , corresponding, for 20 events (the upper limits available for GRB 000214 and GRB 010222 were obviously not included in the correlation analysis) to a chance probability as low as  $1.3 \times 10^{-7}$ . The slope of this relationship is  $0.35 \pm 0.06$ , which is lower than the value found for the 'old' sample (Amati et al. 2002).



**Fig. 1** Isotropic equivalent radiated energy as a function of redshift for the GRBs in our sample. Diamonds (events with firm redshift estimates) and squares (GRB 980326, GRB 980329 and GRB 000214) indicate the events included in the sample of Amati et al. (2002), triangles the new events included in our sample.



**Fig. 2** Peak energy of the intrinsic  $\nu F\nu$  spectrum as a function of Isotropic equivalent radiated energy for the GRBs in our sample. Diamonds and squares (GRB 980326, GRB 980329 and GRB 000214) indicate the events included in the sample of Amati et al. (2002), triangles the new events included in our sample.

## 4 DISCUSSION

With respect to our previous work (Amati et al. 2002), the study reported in this paper is based on a much larger sample (22 against 12 events) and thus the significance of the results is substantially increased. For a discussion of possible selection and data truncation effects,

indicating that they should not affect significantly our results, see Amati et al. (2002), Jimenez, Band & Piran (2001) and Barraud et al. (2003) for the BeppoSAX, BATSE and HETE-2 events, respectively.

The trend of  $E_{\text{rad}}$  with  $z$  may indicate an higher energy budget for older events. In this case, the high dispersion may reflect significant variation in shock parameters, and thus in shock radiating efficiency, and/or in beaming angles, in the case that the assumption of isotropic emission is not valid for several events in our sample. If the emission of most GRBs is collimated and the radiated energy is nearly constant, as supposed e.g. by Frail et al.(2001) , then the observed trend of the *maximum*  $E_{\text{rad}}$  with  $z$  may be due to a combination of the facts that the estimated isotropic equivalent radiated energy is larger for events with smaller jet opening angles and that it is more probable to detect events with small jet opening angles at high  $z$  than at low  $z$ . The hypothesis that older GRBs are more energetic is still valid if we assume that the distribution of jet angles is very narrow.

The reinforced evidence of a correlation between  $E_{\text{p}}^{\text{rest}}$  and  $E_{\text{rad}}$  confirms the indications emerged from the observed hardness-intensity correlation and previous correlation studies on burst energy break, peak flux and fluence performed on events with unknown  $z$ . For example, Lloyd, Petrosian & Mallozzi (2000) , basing on a BATSE sample, inferred  $\log(E_{\text{p}}^{\text{rest}}) \propto d \times \log(E_{\text{rad}})$ , with  $0.4 < d < 0.7$ , which is consistent with our findings. The  $E_{\text{p}}^{\text{rest}} - E_{\text{rad}}$  relationship can put constraints on GRB prompt emission models, like SSM internal shocks, Inverse Compton (IC) dominated internal shocks, external shocks, innermost models (see Zhang & Meszaros 2002 for a review). In general,  $E_{\text{p}}^{\text{rest}}$  and  $E_{\text{rad}}$  are both quantities dependent on the fireball bulk Lorentz factor  $\Gamma$ , in a way varying for each scenario and for different assumptions (e.g. Schaefer 2003 ). For instance, as pointed out by Zhang & Meszaros (2002): a) the correlation we found implies for SSM internal shocks that the slope of the power-law linking  $E_{\text{p}}^{\text{rest}}$  and  $\Gamma$  is  $< 1/4$ , unless invoking relevant IC and/or peculiar assumptions; b) external shocks predict a steeper slope of the  $E_{\text{p}}^{\text{rest}} - E_{\text{rad}}$  power-law relationship with respect to the  $\sim 0.4-0.5$  what we found; c) innermost (i.e. baryon photosphere) emission models predict a slope consistent with our results, but this mechanism is expected to contribute only a fraction of the total GRB prompt emission.

If the emission of the GRBs included in our sample is collimated, then the spread of jet angles, if not too large, may contribute to the scatter around the best fit power-law of the  $E_{\text{p}}^{\text{rest}} - E_{\text{rad}}$  relationship. By assuming, as above, that most events are jetted and radiate a nearly constant energy, then more collimated events have an higher equivalent isotropic radiated energy and thus the true correlation may be between  $E_{\text{p}}^{\text{rest}}$  and the jet opening angle  $\theta_j$  (and the relation between  $\theta_j$  and  $\Gamma$  would also play a role).

The constraints coming from the  $E_{\text{p}}^{\text{rest}} - E_{\text{rad}}$  relationship have to be combined with those coming from the broadness of the  $E_{\text{p}}^{\text{rest}}$  distribution. Indeed, our results indicate that the intrinsic  $E_{\text{p}}^{\text{rest}}$  distribution is broader than inferred from e.g. BATSE bright bursts (Preece et al. 2000), and is thus less critical for the models (the broadness increases with the number of independent parameters of the model, e.g. Zhang & Meszaros 2002).

Finally, the results of the estimation of  $E_{\text{p}}^{\text{rest}}$  for further HETE-2 GRBs with known redshift, remarkably including the X-Ray Flash 020903 (if its redshift estimate is true), confirm the  $E_{\text{p}}^{\text{rest}} - E_{\text{rad}}$  relationship (Lamb, Donaghy & Graziani 2004).

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