Gamma-ray bursts spectral correlations and their cosmological use

BY GIANCARLO GHIRLANDA*

INAF-Osservatorio Astronomico di Brera, Via E Bianchi 46, I-23807 Merate (LC), Italy

The correlations involving the long-gamma-ray bursts (GRBs) prompt emission energy represent a new key to understand the GRB physics. These correlations have been proved to be the tool that makes long-GRBs a new class of standard candles. Gamma Ray Bursts, being very powerful cosmological sources detected in the hard X-ray band, represent a new tool to investigate the Universe in a redshift range, which is complementary to that covered by other cosmological probes (SNIa and CMB). A review of the \(E_p - E_{iso}\), \(E_p - E_\gamma\), \(E_p - E_{iso} - t_{break}\) and \(L_{iso} - E_p - T_0\) correl predictions is presented. Open issues related to these correlations (e.g. presence of outliers and selection effects) and to their use for cosmographic purposes (e.g. dependence on model assumptions) are discussed. Finally, the relevance of thermal components in GRB spectra is discussed in the light of some of the models recently proposed for the interpretation of the spectral-energy correlations.

Keywords: gamma rays: bursts; cosmology; emission mechanism: thermal; non-thermal; X-rays: observations

1. The \(E_p - E_{iso}\) and \(E_p - E_\gamma\) correlations

Long-gamma-ray bursts (GRBs) with spectroscopically measured redshifts show a strong correlation between the total isotropic energy emitted during the prompt phase \(E_{iso}\) and the peak energy of their \(vF_v\) spectrum \(E_p\) computed in the source rest frame. This correlation, discovered by Amati et al. (2002) with 12 long-GRBs detected by BeppoSAX, was confirmed by adding 23 bursts detected by other satellites (Ghirlanda et al. 2004b) and extended to very low energies with few X-ray flashes (Lamb et al. 2004). Figure 1 shows the \(E_p - E_{iso}\) correlation updated to September 2006 with 49 long-GRBs. Since its discovery, only two bursts (GRB 980425 and GRB 031203) appeared inconsistent with this correlation. Since the launch of the Swift satellite in November 2004, only 13 out of approximately 45 bursts with measured redshifts (within the sample of approximately 170 events detected by Swift) were added to the \(E_p - E_{iso}\) correlation. This is mainly due to the narrow energy range (15–150 keV) of the BAT instrument on-board Swift. Indeed, only in five cases (shown in figure 1) was the peak energy measured from the BAT spectrum.

*giancarlo.ghirlanda@brera.inaf.it

One contribution of 35 to a Discussion Meeting Issue ‘Gamma-ray bursts’.
However, the energy derived under the isotropic assumption is huge and widely dispersed (between a few $10^{50}$ and $10^{54}$ erg). If, instead, GRBs are collimated within a jet, the estimated energies and their dispersion are highly reduced, i.e. by a factor $f = (1 - \cos \theta) \approx 10^{-3} - 10^{-2}$ with $\theta \sim 1$–10 deg (Frail et al. 2001). The observable consequence of the jetted nature of GRBs is an (achromatic) break in their afterglow light curves. Assuming a radiative efficiency of the prompt phase (20%) and the density profile of the circum-burst medium, either homogeneous (HM) or wind-like (WM, e.g. scaling as $\rho_{\text{circ}} \propto r^{-2}$), it is possible to estimate the jet opening angle from the measure of the afterglow break time (Sari 1999).

In both scenarios (HM or WM) the collimation-corrected energy $E_\gamma$ is tightly correlated with the peak energy $E_{\text{peak}}$ (Ghirlanda et al. 2004b; Nava et al. 2006). While the $E_p - E_{\text{iso}}$ correlation requires only the knowledge of the GRB prompt emission spectrum and of its redshifts, the $E_p - E_\gamma$ correlation also requires the measure of the jet break time from the afterglow light curve. The $E_p - E_\gamma$ correlation (in the WM case) is represented in figure 1 with the most updated sample of 21 GRBs with measured $t_{\text{jet}}$.

The $E_p - E_\gamma$ correlation in the WM case is linear. This implies that (i) it is invariant for transformation from the source rest frame to the comoving frame (i.e. both $E_p$ and $E_\gamma$ transform $\propto I^{-1}$ if looking at a uniform jet within its opening angle) and (ii) the total number of photons, in different GRBs, is roughly constant $\sim 4 \times 10^{56}$.

Figure 1. Correlation between the $\nu F_\nu$ peak spectral energy and the isotropic energy (on the right side of the plot) defined with 49 GRBs (updated to 15 September 2006). The best fit solid line is $E_p/100$ keV = $3.9 \pm 0.1 (E_{\text{iso}}/1.62 \times 10^{53})^{0.56\pm0.01}$ ($\chi^2=530/47$ d.o.f.) and the pale-orange region represents the $3\sigma$ scatter (computed perpendicular to the best fitting line and modelled as a Gaussian) of the data points around the correlation. The blue points represent the 15 GRBs added since 2005 (i.e. in the Swift "era"). Among these only five bursts had their $E_p$ measured by Swift (red-circled symbols). The two outliers with respect to the $E_p - E_{\text{iso}}$ correlation (GRB 980425 and GRB 031203) are shown. On the left side of the plot is shown the $E_p - E_\gamma$ correlation (computed in the case of a circumburst medium density scaling $\propto r^{-2}$, i.e. wind medium) with the most updated sample of 21 GRBs. The solid line is the best fit to this correlation $E_p/100$ keV = $3.6 \pm 0.2 (E_\gamma/2.69 \times 10^{50})^{0.95\pm0.06}$ ($\chi^2=17.4/19$ d.o.f.) and the colored regions represent the $1,2,3\sigma$ scatter of the data points around it.
Note that the scatter of the collimation corrected correlation is dominated by the statistical errors on the two variables, differently from the $E_p - E_{\text{iso}}$ correlation which has a larger dispersion. The small scatter is what makes the $E_p - E_\gamma$ correlation a distance indicator and allows one to use GRBs as standard candles (Ghirlanda et al. 2004a, 2006a,b; Firmani et al. 2005).

2. Open issues

While possible interpretations of the $E_p - E_{\text{iso}}$ and the $E_p - E_\gamma$ correlations have been recently proposed, there are still several open issues about these correlations and their cosmological use.

(a) Outliers

GRB 980425 and GRB 031203 (both associated with a nearby SN) are respectively five and four orders of magnitude sub-luminous (but with a similar $E_p$) with respect to the population of bursts obeying the $E_p - E_{\text{iso}}$ correlation. It has been proposed that they are normal GRBs observed off-axis (e.g. Ramirez-Ruiz 2005). In this case, however, the true luminosities of these two events (to be consistent with the $E_p - E_{\text{iso}}$ correlation) would make them the most luminous GRBs ever observed at very low redshifts (i.e. 0.0085 and 0.106). This is hardly reconcilable with any conceivable luminosity function. Instead, it might still be the case that they are representative of a different population of local sub-luminous GRBs (e.g. Soderberg et al. 2004).

An alternative explanation (Ghisellini et al. 2006a), which aims at testing if these two events can be consistent with the $E_p - E_{\text{iso}}$ correlation, was motivated by the recent Swift GRB 060218 (Campana et al. 2006) also associated with an SN event at $z = 0.033$. Its total isotropic energy ($\sim 7 \times 10^{49}$ erg) is only slightly larger than that of the two outliers. Nonetheless, its very long duration (3000 s) coupled with a strong hard-to-soft spectral evolution (figure 2) makes its time-averaged spectral peak energy approximately 5 keV, i.e. fully consistent with the $E_p - E_{\text{iso}}$ correlation.

Using GRB 060218 as a template, we tried to model the spectral evolution of GRB 031203 and 980425 with the available data. It turns out that in these two bursts a strong spectral evolution might have caused part of their energy to be emitted in the soft X-ray band, where it went undetected. In the case of GRB 031203 (figure 3), indeed, there is evidence that a late time soft X-ray fluence, comparable to that observed in the $\gamma$-ray band, might be responsible for the observed dust scattering halo evolution (Tiengo & Mereghetti 2006). As a result, the total energy of these two events is only slightly larger than that measured from their $\gamma$-ray spectra, while their peak energy is considerably (a factor 10–20) smaller.

(b) Selection effects

It has been argued that different samples of BATSE bursts, without a redshift measure, are inconsistent with the $E_p - E_{\text{iso}}$ correlation for any distance at which they might be located (Band & Preece 2005; Nakar & Piran 2005; Kaneko et al. 2006).
We note that (i) the updates of the $E_p - E_{iso}$ correlation (Ghirlanda et al. 2004b; Lamb et al. 2005; Amati 2006 and the present paper—figure 1), i.e. from 12 to 49 events, show that all bursts with measured $z$ and spectral properties do follow this relation (i.e. the outliers are still only two bursts); (ii) a test (Ghirlanda et al. 2005a,b) performed with 442 GRBs for which only a pseudo redshift estimate is available (from the Lag-Luminosity correlation—Norris et al. (2000)), has confirmed that these bursts still define a correlation in the $E_p - E_{iso}$ plane. This correlation has a similar slope and a different normalization (but only a slightly larger scatter) with respect to the correlation defined with the GRBs with spectroscopically measured redshifts. On the other hand, Band & Preece (2005) and Nakar & Piran (2005) were unable to argue that more than a small fraction of GRBs are inconsistent with the $E_p - E_{iso}$ correlation. Therefore, if we assume that the $E_p - E_{iso}$ correlation is true, we can derive from a given $E_{iso}$ its isotropic equivalent. If the GRB angle distribution were uniform the probability of deriving any value of $E_{iso} = E_{iso}/f$ would be equal. This would produce a random (nearly) uniform scatter of data points in the $E_p - E_{iso}$ plane. Instead, if the angle distribution is peaked, we should find a clustering of the data points.

Figure 2. GRB 060218. (a) XRT and BAT spectra. Each spectrum is fitted with a cutoff-powerlaw plus a black body component (whose nature is discussed elsewhere, e.g. Campana et al. 2006; Ghisellini et al. 2006b). Early and late time spectra (blue and green symbols) show a strong spectral evolution: the powerlaw spectral index and the $vF_v$ peak energy soften, the latter moving from the 15–150 keV BAT energy range to the 0.3–10 keV XRT band. The red spectrum is integrated over the 3000 s of duration of the burst and its cutoff-powerlaw model peaks at $E_p \sim 5$ keV. (c) Show the XRT and BAT light curves and the peak energy evolution. These are fitted self-consistently with the parameters evolving as shown in (b).
around some correlation. The comparison of the angle distribution of the 442 GRBs with pseudo redshifts is indeed peaked (figure 4). The different average angle of the two distributions might be due to the preference of detecting the most luminous GRBs, i.e. those with (on average) a smaller jet opening angle.

(c) Model dependence of the $E_p - E_\gamma$ correlation

The $E_p - E_\gamma$ correlation is derived in the standard uniform jet scenario assuming a constant radiative efficiency and a circumburst medium density profile. Although the present afterglow observations do not allow one to distinguish between the homogeneous and the wind density circumburst scenarios, the properties of the $E_p - E_\gamma$ correlation (small scatter and linear slope) derived in the WM case are appealing (Nava et al. 2006) also for the improvement of the cosmological constraints (Ghirlanda et al. 2006b). However, the model dependence of this correlation still represents one of its main weak points. Liang & Zhang (2005) discovered a completely empirical correlation $E_{iso} \propto E_p^{2} t_{break}^{-1}$ (figure 4; Nava et al. 2006). Through this correlation, it is possible to derive cosmological constraints, which are consistent with those obtained with the two (HM and WM) model dependent $E_p - E_\gamma$ correlations. It has been
demonstrated (Nava et al. 2006) that the $E_p - E_{iso} - t_{break}$ correlation is fully consistent with the two model dependent correlations and this strengthens the possibility of using GRBs as standard candles. One of the main still open issues related to the $E_p - E_{iso}$ and $E_p - E_{iso} - t_{break}$ correlations is the fact that they require the measure of the afterglow jet break time $t_{break}$. While most of the jet breaks of the ‘gold’ sample of 21 bursts used to define these correlations are derived from the optical afterglow light curves, there is growing evidence that some Swift bursts do not clearly show a break in their X-ray and optical light curves when it should be expected according to these correlations.

Although the lack of jet break times is still an open issue to be investigated, the use of GRBs as standard candles has been definitely confirmed by the recent discovery of a new correlation, which is not affected by this problems. Firmani et al. (2006b) found that there is a very tight correlation between the GRB isotropic luminosities $L_{iso}$, the peak energy $E_p$ and a characteristic time-scale of the prompt emission light curve $T_{0.45}$ (figure 5). The latter parameter was originally defined to compute the GRB variability (Reichart et al. 2001), which is indeed correlated with the GRB luminosity. This new $L_{iso} - E_p - T_{0.45}$ correlation, being model independent and assumption-free, solves the previous problems. Moreover, the cosmological constraints derived with this correlation, though still based on a small sample of GRBs, are tighter than those obtained with the $E_p - E_{\gamma}$ correlations (Firmani et al. 2006a). The larger redshift extension of GRBs with respect to SNIa and the fact that the $L_{iso} - E_p - T_{0.45}$

Figure 4. (a) Jet opening angle distribution of 21 GRBs with measured $z$ and $t_{break}$ (dashed line). The opening angle distribution of the large sample of 442 GRBs with pseudo-$z$ measured from the Lag-Luminosity correlation (Band et al. 2004) is shown (solid line histogram) together with its log-normal fit (solid line—$\langle \theta_{jet} \rangle \sim 6$ deg). (b) The $E_p - E_{iso} - t_{break}$ correlation. The best fit is $E_{iso} = 1.12 \pm 0.11 (E_p/295 \, \text{keV})^{1.93 \pm 0.17} \cdot (t_{jet} / 0.51d)^{-1.08 \pm 0.17}$, where primed quantities are in the source rest frame.
correlation is based only on prompt emission properties (i.e. related to the detection of the GRB prompt emission in the $\gamma$-ray band), makes GRBs a new cosmological tool complementary to SNIa. By adding 19 GRBs to the sample of 115 SNIa (Astier et al. 2006) the constraints on the $\Omega_M$-$\Omega_A$ (as well as on the parameters describing the dark energy equation of state—Firmani et al. (2006a)) are considerably improved (figure 5) and show that GRBs and SNIa seem to prefer the $\Lambda$CDM model.

correlation is based only on prompt emission properties (i.e. related to the detection of the GRB prompt emission in the $\gamma$-ray band), makes GRBs a new cosmological tool complementary to SNIa. By adding 19 GRBs to the sample of 115 SNIa (Astier et al. 2006) the constraints on the $\Omega_M$-$\Omega_A$ (as well as on the parameters describing the dark energy equation of state—Firmani et al. (2006a)) are considerably improved (figure 5) and show that GRBs and SNIa seem to prefer the $\Lambda$CDM model.

(d) Thermal components in GRB spectra and the interpretation of the $E_p - E_{iso}$, $E_p - E_{\gamma}$, $L_{iso} - E_p - T_{0.45}$ correlations

Among the proposed interpretations of the above correlations (Eichler & Levinson 2004; Toma et al. 2005), Rees & Meszaros (2005) suggested that a thermal black body spectrum is the most natural way to link the peak spectral energy and the total luminosity of GRBs as shown by the $E_p - E_{iso}$ correlation (see also Thompson 2006; Thompson et al. submitted). This ‘thermal’ interpretation requires that the prompt emission spectrum of GRBs is dominated by a thermal black body that determines the peak of the $\nu F_{\nu}$ spectrum. Thermal emission is expected in the standard ‘hot’ fireball model (Goodman 1986): it is the initial black body, which survived to the conversion (during the opaque-acceleration phase) into bulk kinetic energy. An alternative scenario (Rees & Meszaros 2005) proposes that the thermal photons are created by dissipation below the GRB photosphere.
Evidences of the presence of a thermal black body component were discovered in the BATSE spectra (Ghirlanda et al. 2003; Ryde 2004) although this component dominated the initial phase of approximately 2 s of the prompt emission. During this phase, it was shown that the luminosity and the temperature evolve similarly in different GRBs, while the late time spectrum is dominated by a non-thermal component (e.g. fitted with the empirical Band et al. (1993) model). Attempts to deconvolve these spectra with a mixed model, i.e. a thermal black body and a non-thermal powerlaw (Ryde 2005), showed that the presence of the black body component (with a monotonically decreasing flux) could be extended to the late prompt emission phase (see also Bosnjak et al. 2005).

In order to test the applicability of the thermal interpretation to the $E_p - E_{\text{iso}}$, $E_p - E_\gamma$, $L_{\text{iso}} - E_p - T_{0.45}$ correlations, we have been verifying whether a thermal component can be fitted to the spectra of the bursts that are used to define these correlations (Bosnjak et al. 2006). Ryde (2005) showed that the mixed model fits to the time resolved spectra of GRBs is almost equivalent to a fit with a non-thermal model ‘a la Band’. We, therefore, selected the 10 GRBs on the $E_p - E_{\text{iso}}$ correlation detected by BATSE: these data allow one to analyse the spectral evolution with adequate spectral resolution. These spectra are inconsistent with a single black body model, while we succeeded in fitting a thermal black body component plus a powerlaw. In general (as also found by Ryde (2005) in few

Figure 6. Prompt emission spectrum of GRB 990123 time-averaged over its duration: BATSE/CGRO data (black points) and WFC/BeppoSAX data (green points). Solid blue line is the best fit with the non-thermal Band empirical model. The fit of the BATSE data alone with the mixed model (i.e. black body + powerlaw) is good (solid red line) but the resulting powerlaw component is inconsistent with the WFC data. Note also that the WFC and BATSE (low energy) data are consistent with a single powerlaw ($EF(E) \propto E^{1.15}$, which excludes the possibility that it is the self absorbed synchrotron emission) extending from 2 keV to few hundred keV. Solid orange lines are the model fits with the mixed black body + powerlaw model to the time resolved spectra covering the duration of the burst. Their sum is represented by the dot-dashed red line.

Phil. Trans. R. Soc. A (2007)
GRBs), the powerlaw component softens during the burst being (on average) \( F(E) \propto E^{-0.5} \) at the very beginning. The black body also evolves in time and comprises at most ca 50% of the total spectral flux. However, such a soft non-thermal powerlaw component should dominate the spectrum in the X-ray energy band. We found that in 5/10 GRBs, there are also X-ray data from the BeppoSAX/WFC (2–28 keV) and in all these cases the data of the WFC were inconsistent with the extrapolation in the 2–28 keV band of the powerlaw fitted to the BATSE \( \gamma \)-ray data. Moreover, the X-ray to \( \gamma \)-ray (WFC+BATSE) broad band spectrum is consistent with a single non-thermal fit (with the Band model) with a low energy spectral component much harder than the powerlaw of the mixed model. An example is shown in figure 6. These results represent a challenge to the presence of a dominating black body component in these bursts.

I am grateful to G. Ghisellini, C. Firmani, F. Tavecchio, A. Celotti, L. Nava, M. Nardini and Z. Bosnjak for years of fruitful collaboration. I am also grateful to M. L. and T. Smith for the valuable logistic support during my stay in London.

References