1

# GRB 060218 and the outliers with respect to the $E_{ m p}-E_{ m iso}$ correlation

G. Ghirlanda & G. Ghisellini

Osservatorio Astronomico di Brera Merate, I-23807, via E. Bianchi 46 E-mail: giancarlo.ghirlanda@brera.inaf.it

GRB 031203 and GRB 980425 are the two outliers with respect to the  $E_{\rm p}-E_{\rm iso}$  correlation of long GRBs. Recently Swift discovered a nearby extremely long GRB 060218 associated with a SN event. The spectral properties of this bursts are striking: on the one hand its broad band SED presents both thermal and non–thermal components which can be interpreted as due to the emission from the hot cocoon surrounding the GRB jet and as standard synchrotron self absorbed emission in the GRB prompt phase, respectively; on the other hand it is its long duration and its hard–to–soft spectral evolution which make this underluminous burst consistent with the  $E_{\rm p}-E_{\rm iso}$  correlation of long GRBs. By comparing the available spectral informations on the two major outliers we suggests that they might be twins of 060218 and, therefore, only apparent outliers with respect to the  $E_{\rm p}-E_{\rm iso}$  correlation. This interpretation also suggests that it is of primary importance the study the broad band spectra of GRBs in order to monitor their spectral evolution throughout their complete duration.

Keywords:

## 1. The peak spectral energy – isotropic energy in GRBs

Long–duration Gamma Ray Bursts (GRBs) present a correlation between the peak energy of their  $\nu F_{\nu}$ spectra ( $E_{\rm peak}$ ) and their isotropic equivalent energy ( $E_{\rm iso}$ ) emitted during the prompt phase.<sup>1</sup> This correlation (presented in Fig.1) has been updated since its discovery<sup>1</sup> by adding more than 38 GRBs with measured redshifts and well constrained spectral properties.<sup>3–5</sup> For a subsample of these events it was also possible to estimate their jet opening angles by measuring the jet break time of their (optical) light curves. The correction of the isotropic energy for the collimation factor led to the discovery of a very tight (i.e. the  $E_{\rm p}-E_{\gamma}$ , <sup>4,6</sup>) correlation which has been used to make GRBs standard candles (<sup>7,8</sup>). However, since

the discovery of these correlations, GRB 980425 and GRB 031203 resulted inconsistent with them.

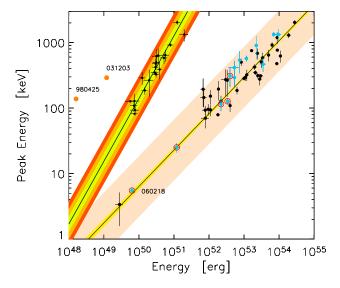
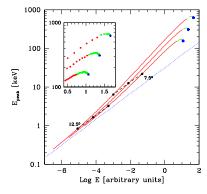


Fig. 1. Correlation between the  $\nu F_{\nu}$  peak spectral energy and the isotropic energy (on the left side of the plot) defined with 49 GRBs (updated to 15 Sept. 2006). The blue points represent the 15 GRBs added since 2005 (i.e. in the Swift "era") and the 5 events whose peak energy was measured by Swift are shown with red–circled blue points. The outliers (GRB 980425 and GRB 031203) are shown. On the left side of the plot it is shown the  $E_{\rm p}-E_{\gamma}$  correlation.

GRB 980425 and 031203 are associated with a nearby SN event (at z=0.0885 and z=0.106, respectively). However, there are at least three events which obey the  $E_{\rm p}-E_{\rm iso}$  correlation and are associated with a SN event (030329, 021211 and 060218). Among these the most recently discovered (060218, Campana et al. 2006) could guide us towards the understanding of the nature of the two outliers.

It has been proposed<sup>9,10</sup> that the two outliers could be normal GRBs observed off axis (with a typical viewing angle twice their jet opening angle).



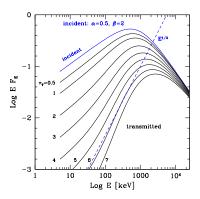


Fig. 2. Left: The peak of the observed spectrum  $E_{\rm peak}$  as a function of the time integrated flux E. Both depend on the viewing angle  $\theta_{\rm v}$ . In the insert we show a zoom for small viewing angles, within (green dots) and outside  $\theta_{\rm j}$ . We assumed  $\theta_{\rm j}=5^{\circ}$ ,  $0<\theta_{\rm v}<20^{\circ}$ ,  $\alpha_1=0.5$ ,  $\alpha_2=2$ . The dotted line, shown for comparison, has a 1/3 slope. The three lines have  $\Gamma=50$ , 100 and 200, and  $E'_{\rm peak}=1.25$  keV. Black points, connected with dashed lines, correspond to the same viewing angle  $\theta_{\rm v}=(7.5,12.5)$  for the three different choices of  $\Gamma$ . Right: Transmitted spectrum for different values of the Thomson optical depth  $\tau_{\rm T}$ , as labeled. The incident spectrum has  $E_{\rm peak}=511$  keV,  $\alpha=0.5$  and  $\beta=2$ .

In this scenario we can reconstruct the true energetic and peak energy of these two events if they were observed on axis<sup>11</sup> by correcting for the debeaming effect (Fig.2 left panel). It turns out that the two outliers should be the most luminous events in the population of bursts though being the closest (980425 is the record-holder) GRBs ever detected.

An alternative possibility is that these two bursts appear underluminous because their radiation is highly absorbed by material located in their vicinity (as proposed by  $^{13,14}$ ). The spectrum produced by the central source is modified by the scattering screen (Fig.2 right panel): for increasing optical depths the transmitted spectrum has a harder low energy component and a harder peak energy (with respect to the incident spectrum) due to the energy dependent Klein–Nishina absorption. In this scenario the two outliers would require a scattering material of  $\tau$  between 6 and 8 to become consistent with the  $E_{\rm p}-E_{\rm iso}$  correlation.

### 2. GRB 060218: a long burst with a peculiar SED

GRB 060218 (z = 0.033, 18), associated to SN 2006aj 15 is a long duration event (>3000 s) detected by *Swift* BAT and followed with a few hundred

seconds delay by the XRT and UVOT telescopes on–board  $Swift.^2$  The broad band Optical to X–ray SED of GRB 060218 (Fig.3 left panel) presents some interesting features: (i) a (steady) thermal component in the X–ray with typical temperature of  $\sim 0.2$  keV and a total energy of  $\sim 10^{49}$  erg; (ii) a non–thermal X–ray component softening with time and (iii) a (steady) opt-UV spectrum which is well described by the Rayleigh–Jeans tail of a black body.

The presence of a Black Body component has been interpreted<sup>2</sup> as the SN shock breakout (SNSB) emission, which has never been observed before.

As shown in Fig.2 (left panel), the opt–UV spectrum lies above the extrapolation of the X–ray Black Body. Instead, a single Black Body (whose Rayleigh–Jeans tail matches the opt-UV data) is inconsistent with the X–ray spectrum. Moreover, the latter possibility requires that the Black Body luminosity is  $10^{48}$  erg/s. Considering the exceptional duration of this burst (i.e.  $> 10^3$  s) this would imply that, if this is the energy produced by the subrelativistic SN shock breakout, it would exceed the total kinetic energy of the SN (i.e.  $\sim 10^{51}$  erg) estimated from the late time optical spectroscopy. <sup>15</sup>

On the other hand it might still be possible that either the X-ray or the opt-UV Black Body component are the SNSB. Nonetheless, in the first case the velocity of the emitting material  $(v = (L_{BB}/4\pi t^2\sigma_r T_{BB}^4)^{1/2})$  is very low ( $\sim 3000 \text{ km/s}$ ) compared to the velocity derived from the optical spectroscopy ( $\sim 20.000 \text{ km/s} \text{ s}^{-16}$ ). In the second case, instead, the Black Body temperature should not be much above the UV frequency (to limit the total energetic) but the velocity derived (if the SN exploded simultaneously to the GRB) is larger than c. Moreover, detailed numerical modeling of the SNSB (Li 2006) predicts lower luminosity and duration and larger temperatures for the X-ray emission of the SNSB than what observed.

We have instead proposed<sup>12</sup> that the opt–UV spectrum and the non–thermal contemporaneous X–ray emission of GRB 060218 can be well fitted with a synchrotron–self–absorbed model (Fig.3 right panel): in this case the self–absorption frequency falls just above the opt-UV band. The X–ray Black Body component, instead, is the thermal emission from the hot cocoon surrounding the jet (e.g.<sup>17,19</sup>).

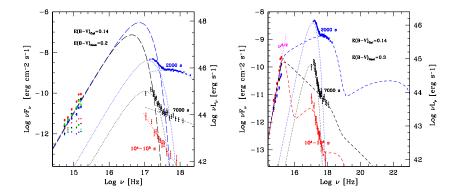


Fig. 3. Left: The SED of GRB 060218 at different times. Blue: 2000 s (integrated for  $\sim 400$  s for the X-ray); black: 7000 s (integrated for  $\sim 2500$  s); red: 40,000 s; green:  $1.2 \times 10^5$  s (only UVOT data are shown). The opt–UV data are taken from C06 while the X-ray data have been re-analysed by us. The optical–UV data lie above the blackbody found by fitting the X-ray data (dotted lines). Instead, the opt–UV data seem to identify another Black Bodycomponent (long-dashed lines) which is inconsistent with the X-ray data at the same epochs. Small crosses without error bars are UVOT data not deabsorbed. De-absorbed data [with a galactic E(B-V)=0.14 plus a host E(B-V)=0.2] are shown with error bars. Right: The SED of GRB 060218 at different times, as in Fig. 1, but with the optical UV points de-reddened with  $E(B-V)_{\rm host}=0.3$  instead of 0.2 This produces an opt–UV spectrum  $\propto \nu^{5/2}$ . We also show the SSC model, discussed in the text, for the 3 SEDs for which we have simultaneous UVOT, XRT data (i.e. at 2000, 7000 and  $\sim 10^4-10^5$  seconds after trigger).

### 2.1. The spectral evolution of GRB 060218

The most striking spectral property of GRB 060218 is that its spectrum evolves from the hard BAT energy band to the soft XRT band. For this reason the time–integrated spectrum of this burst has a peak energy in the soft X–ray band at 5 keV. Considering its relatively low luminosity (i.e.  $\sim 10^{49}$  erg - similar to that of the two outliers), its low  $E_{\rm peak}$  is what makes it consistent with the  $E_{\rm p}-E_{\rm iso}$  correlation. In Fig.4 we show two spectra (corresponding to the initial and the final emission of the burst) and its time integrated spectrum. The other panels show the fit with a model that reproduces the spectral evolution and the light curve in the 0.2-10 keV and 15-150 keV band and the time evolution of the  $E_{\rm peak}$ .

In particular the presence of nearly simultaneous observations of the burst prompt emission by the XRT instrument on–board *Swift* was the key to classify this burst as being consistent with the  $E_{\rm p}-E_{\rm iso}$  correlation:

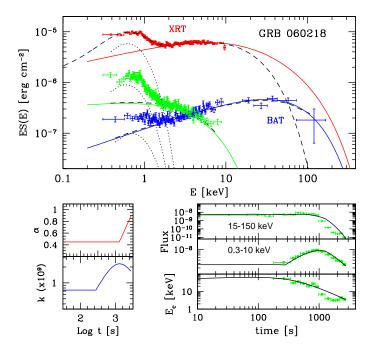


Fig. 4. Top panel: Spectra of GRB 060218 for different time-bins: i) entire duration (top); ii) [159–309 s] (rising spectrum with also BAT data) iii) [2456–2748 s] (soft spectrum). We plot ES(E) vs E, S(E) being the fluence. Dotted lines indicate the blackbody component, not considered for the spectral evolution, and long-dashed lines represents the best fit obtained from the analysis of the data. Continuous lines show the results of our proposed modeling. Left bottom panel: assumed behaviour of the normalisation K and energy spectral index  $\alpha$ . Right bottom panel: light curves in the BAT (15–150 keV) and XRT (0.3–10 keV) range, and evolution of  $E_c$ . The flux in the 0.3–10 keV is the (de–absorbed) flux of the cut–off power law component only: we have subtracted the blackbody component from the total flux. Continuous lines are the results of our modelling.

in fact, if only BAT measured its spectrum, we would have classified this event as the third outlier with respect to the  $E_{\rm p}-E_{\rm iso}$  correlation, with  $E_{\rm peak}\sim 100~{\rm keV}$  and  $E_{\rm iso}\sim 7\times 10^{48}~{\rm erg}$ .

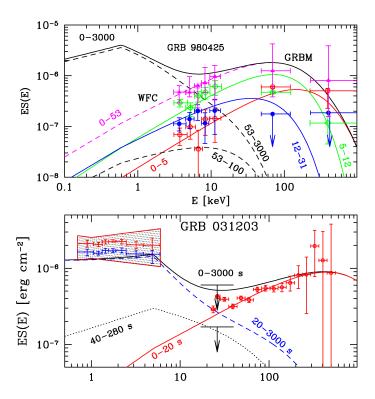


Fig. 5. Top panel: spectral evolution of GRB 980425. The data are from BeppoSAX(WFC: 2-28 keV and GRBM: 40-700 keV adapted from Frontera et al. 2000). The model fits (lines) are obtained with the same model used for GRB 060218 by simultaneously fitting the light curves and the available spectra of GRB 980425. Bottom panel: spectral evolution of GRB 031203. In this case the late time spectrum should produce a considerable flux in the X-ray band to be consistent with the observed evolution of its dust scattering halo.  $^{20}$ 

#### 3. GRB031203 & GRB980425 become mainstream

We have verified if GRB 031203 and GRB980425 have a spectral evolution consistent with that of 060218 (i.e. hard to soft). If this is the case it is possible that their soft late—time emission went undetected in the soft X—ray instruments on board Integral and BeppoSAX, which detected these two events. Interestingly, GRB 031203 (Fig.5) produced a spectacular dust scattering halo (observed with XMM—Newton) which evolved in time. The spectral flux responsible of the halo should have had a fluence similar to that of the prompt emission detected by Integral. This has two effects:

on the one side the total energy is larger than that measured from the Integral spectrum alone while, on the other side, the peak energy of the time integrated spectrum is in the X–ray band. This two effects combined make GRB 031203 consistent with the  $E_{\rm p}-E_{\rm iso}$  correlation.

In the case of GRB 980425 our model predicts a considerable long duration of the burst with a spectrum peaking in the soft X-ray band at late times. Unfortunately there are no data confirming this possibility (as opposed to the case of 031203) and we are therefore forced to assume that this burst lasted more than what the WFC on–board BeppoSAX could monitor.

## Acknowledgments

We are grateful to F. Tavecchio, C. Firmani, Z. Bosnjak for fruitful collaborations.

#### References

- 1. Amati, L., Frontera, F., Tavani, M., et al. 2002, A&A, 390, 81
- 2. Campana, S., Mangano, V., Blustin, A.J., et al., 2006, Nature, 442, 1008
- 3. Amati L. 2006, A&A, 372, 233
- 4. Ghirlanda G., Ghisellini G. & Lazzati D. 2004, ApJ, 616, 331
- 5. Lamb D. Q., Donaghy T. Q. & Graziani C. 2004 NewAR, 48, 459
- 6. Nava L. et al., 2004, A&A, 450, 471
- 7. Ghirlanda G. et al. 2004a, ApJ, **613**,L13
- 8. Firmani C. et al. 2005, MNRAS, 360, L1
- 9. Eichler D. & Lenvinson A. 2004, ApJ, **614**, L13
- 10. Ramirez-Ruiz E., 2005, ApJ, 625, L91
- 11. Ghisellini G., et al., 2006, MNRAS, 372, 1699
- 12. Ghisellini G, Ghirlanda G. & Tavecchio F. 2006a, MNRAS, 375, L36
- 13. Barbiellini, G. et al., MNRAS, 350, L5
- 14. Brainerd, J.J., 1994, ApJ, 428, 21
- 15. Mazzali, P. et al., 2006, Nature, 442, 1018
- 16. Pian, E. et al., 2006, Nature, 442, 1011
- 17. Fan, Y-Z., Piran, T. & Xu, D., 2006, JCAP, 9, 13
- 18. Mirabal, N., et al., 2006, ApJ, **643**, L99
- 19. Ramirez-Ruiz, E., Celotti, A. & Rees, M.J., 2002. MNRAS, 337, 1349
- 20. Tiengo, A. & Mereghetti, S., A&A, 449, 203