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On the consistency of peculiar GRBs 060218 and 060614 with the $E_{p,i} - E_{iso}$ correlation

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ABSTRACT

We analyze and discuss the position of GRB 060218 and GRB 060614 in the $E_{p,i} - E_{iso}$ plane. GRB 060218 is important because of its similarity with GRB 980425, the prototypical event of the GRB–SN connection. While GRB 980425 is an outlier of the $E_{p,i} - E_{iso}$ correlation, we find that GRB 060218 is fully consistent with it. This evidence, combined with the "chromatic" behavior of the afterglow light curves, is at odds with the hypothesis that GRB 060218 was a "standard" GRB seen off-axis and supports the existence of a class of truly sub-energetic GRBs.

GRB 060614 is a peculiar event not accompanied by a bright supernova. Based on published spectral information, we find that also this event is consistent with the $E_{p,i} - E_{iso}$ correlation. We discuss the implications of our results for the rate of sub-energetic GRBs, the GRB/SN connection and the properties of the newly discovered sub-class of long GRBs not associated with bright supernovae. We have included in our analysis other recent GRBs with clear evidence (or clear evidence of lack) of associated SNe.

Key words. gamma rays: bursts – gamma rays: observations – stars: supernovae: general

1. Introduction

Almost a decade of optical, infrared and radio observations of gamma-ray bursts (GRBs) has allowed to link long-duration GRBs (or, at least, a fraction of them) with the death of massive stars. This result is based on three pieces of evidence: i) there are (to date) four clear cases of association between "broad lined" supernovae (BL-SNe) (i.e. SNe-Ib/c characterized by a large kinetic energy, often labeled as hypernovae, HNe hereafter) and GRBs: GRB 980425/SN 1998bw (Galama et al. 1998), GRB 030329/SN 2003dh (Stanek et al. 2003; Hjorth et al. 2003), GRB 031203/SN 2003lw (Malesani et al. 2004) and GRB 060218/SN 2006aj (Masetti et al. 2006; Campana et al. 2006; Pian et al. 2006); ii) in a few cases, spectroscopic observations of bumps observed during the late decline of GRB afterglows revealed the presence of SN features (Della Valle et al. 2003, 2006a; Soderberg et al. 2005); iii) long GRBs are located inside star forming galaxies (Djorgovski et al. 1998; Le Floc'h et al. 2003; Christensen et al. 2004; Fruchter et al. 2006). The standard theoretical scenario suggests that long GRBs are produced in the collapse of the core of H/He stripped-off massive stars (possibly Wolf–Rayet, see Campana et al. 2006) with an initial mass higher than $\sim 20~M_\odot$ and characterized by a very high rotation speed (e.g. Woosley 1993; Paczyński 1998).

GRB 980425 was not only the first example of the GRB–SN connection, but also a very peculiar event. Indeed, with a redshift of 0.0085, it was much closer than the majority of GRBs with known redshift ($\sim 0.1 < z < 6.3$) and its total radiated energy under the assumption of isotropic emission, E_{iso}, was very low ($\sim 10^{48}$ erg), therefore well below the typical range for "standard" bursts ($\sim 10^{51} - \sim 10^{54}$ erg). Moreover, this event was characterized by values of $E_{p,i}$, the photon energy at which the νF_ν spectrum peaks (hence called *peak energy*), and E_{iso} completely inconsistent with the $E_{p,i} \propto E_{iso}^{0.5}$ correlation holding for long "cosmological" GRBs (Amati et al. 2002).

This correlation has not only several implications for the physics, jet structure and GRBs/XRFs unification scenarios, but can be used to investigate the existence of different sub-classes of GRBs (e.g. Amati 2006). In addition to GRB 980425, also GRB 031203/SN 2003lw (Sazonov et al. 2004; Malesani et al. 2004) was characterized by a value of $E_{p,i}$ which, combined with its low value of E_{iso}, makes it the second (possible) outlier of the $E_{p,i} - E_{iso}$ correlation (the $E_{p,i}$ value of this event is still debated, see, e.g., Watson et al. 2006). Both cases may point towards the existence of a class of nearby and intrinsically faint GRBs with different properties with respect to "standard" GRBs. However, it has been suggested by several authors that the low measured E_{iso} of these events and their inconsistency with the $E_{p,i} - E_{iso}$ correlation are due to viewing angle effects (off–axis scenarios, see, e.g., Yamazaki et al. 2003; Ramirez-Ruiz et al. 2005).

In this paper we focus on the the position, in the $E_{p,i} - E_{iso}$ plane, of two recently discovered events: GRB 060218 and GRB 060614. GRB 060218 is particularly important because of its association with SN 2006aj at $z = 0.033$ (Masetti et al. 2006; Campana et al. 2006; Soderberg et al. 2006a; Pian et al. 2006;
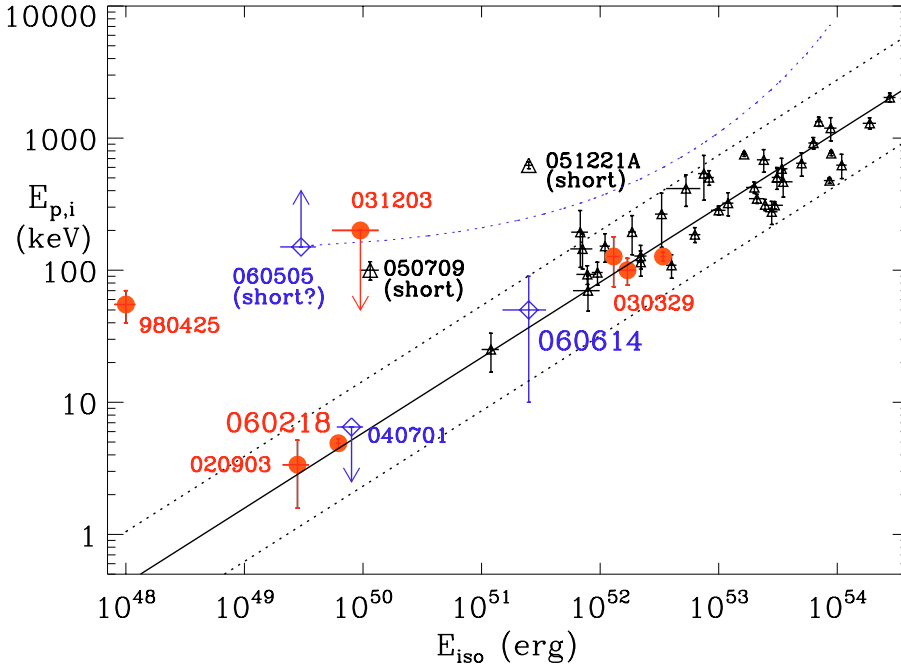
Fig. 1. Distribution of $E_{p,i}$ and E_{iso} values of GRBs and XRFs with firm estimates of z and $E_{p,i}$, including also two short GRBs with known redshift: GRB 050709 and GRB 051221A. Data and models are taken from Amati (2006), except for GRB 060218, GRB 040701 and GRB 060614 (see text). The solid line shows the best-fit power-law obtained by Amati (2006) without including GRB 060218, GRB 980425 and GRB 031203; the two parallel dotted lines delimit the 2-σ confidence region. Those GRBs with evidence of association with a SN (Table 1) are marked with big dots. The location in the $E_{p,i} - E_{iso}$ plane of GRB 060614 and of the other two events with deep limits to the magnitude of the associated SN, XRF 040701 and GRB 060505, are shown as big diamonds. The curved dotted line shows how the GRB 060505 point moves in the $E_{p,i} - E_{iso}$ plane as a function of redshift.

Modjaz et al. 2006; Sollerman et al. 2006; Mirabal et al. 2006; Cobb et al. 2006; Ferrero et al. 2006). In addition, this GRB event was both "local" and "sub-energetic" like GRB 980425 and GRB 031203, but unlike them it matches the $E_{p,i}$ vs. E_{iso} relationship. GRB 060614 is very interesting because of the very deep upper limits to the luminosity of any possibly associated SN (Della Valle et al. 2006b; Fynbo et al. 2006; Gal-Yam et al. 2006). We find that also this event is consistent with the $E_{p,i} - E_{iso}$ correlation (Sect. 3.4). Our analysis includes also other GRBs with evidence for associated SNe and two nearby GRBs which are not accompanied by bright SN explosions. We discuss the implications of our results for the existence and rate of sub-energetic GRBs, the GRB/SN connection and the properties of the sub-class of long GRBs not associated with bright supernovae.

Throughout this paper we assumed $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$.

2. Peculiar GRBs in the $E_{p,i} - E_{iso}$ plane

2.1. GRB 060218, sub-energetic GRBs and GRB/SN events

GRB 060218 was detected by Swift/BAT on 2006 February 18, at 03:34:30 UT and fast pointed and localized by Swift/XRT and UVOT (Cusumano et al. 2006a). The prompt event was anomalously long ($T_{90} = 2100 \pm 100$ s) and very soft (average 15–150 keV photon index of ~2.5), with a 15–150 keV fluence of $(6.8 \pm 0.4) \times 10^{-6}$ erg cm^{-2} (Sakamoto et al. 2006). The spectrum of the host galaxy showed narrow emission lines at a redshift $z = 0.033$ (Mirabal et al. 2006), whereas the optical counterpart showed a blue continuum and broad spectral features characteristic of a supernova (Pian et al. 2006; Modjaz et al. 2006; Sollerman et al. 2006; Ferrero et al. 2006). Similarly to GRB 980425 and GRB 031203, GRB 060218 exhibited a very low afterglow kinetic energy (~100 times less than standard GRBs), as inferred from radio observations (Soderberg et al. 2006b). Based on Swift/BAT and XRT preliminary results (Sakamoto et al. 2006; Cusumano et al. 2006), Amati et al. (2006) argued that the GRB 060218 properties were consistent with the $E_{p,i} - E_{iso}$ correlation. This result is confirmed after

adopting the refined Swift/XRT and BAT data (Campana et al. 2006). Figure 1 shows the position of GRB 060218 in the $E_{p,i}$ vs. E_{iso} plane to be fully consistent with the $E_{p,i} - E_{iso}$ correlation. When adding this event to the sample of Amati (2006), the Spearman rank correlation coefficient between $E_{p,i}$ and E_{iso} turns out to be 0.894 (for 42 events), corresponding to a chance probability as low as $\sim 2 \times 10^{-15}$. Figure 1 also shows that another very soft and weak event, XRF 020903, matches the $E_{p,i} - E_{iso}$ correlation (Sakamoto et al. 2004). Thus, XRF 020903 and GRB 060218 may simply represent the extension to low energy ($E_{iso} < 10^{51}$ erg) of the "cosmological" GRB sequence. In addition, based on the lack of a break in the radio light curve, a lower limit of 1–1.4 rad can be set to to the jet half-opening angle θ_{jet} (Soderberg et al. 2006). This value is much higher than those of classical, cosmological GRBs (e.g. Nava et al. 2006), further supporting the idea that close-by, sub-energetic GRBs have a much less collimated emission (Soderberg et al. 2006b; Guetta & Della Valle 2006). This also implies that the collimation-corrected energy, E_{jet}, released during prompt emission is not much lower than E_{iso}, lying in the range (~ 2.7–6.5) $\times 10^{49}$ erg.

A different (well known) behaviour is exhibited by GRB 980425. Less straightforward is the interpretation of the position of GRB 031203. Based on the detection by XMM–*Newton* of a transient dust-scattered X-ray halo associated with it, some authors (Vaughan et al. 2004; Ghisellini et al. 2006; Watson et al. 2006; Tiengo & Mereghetti 2006) argued that this event might have been much softer than inferred from INTEGRAL/ISGRI data (Sazonov et al. 2004). Finally, we plot in Fig. 1 also short GRBs with known redshift (namely GRB 050709 and GRB 051221A) which lie outside of the region populated by long events (see also Amati 2006).

2.2. GRB 060614 and other no-hypernova events

GRB 060614 was detected by Swift/BAT on June 14, 2006 at 12:43:48 UT as a long (120 s) event showing a bright initial flare followed by softer, extended prompt emission (Parsons et al. 2006). Follow-up observations of the bright X-ray and optical counterparts detected and localized by XRT and UVOT led to the identification of a host galaxy lying at $z = 0.125$

Table 1. *Upper panel*: properties of GRBs with known z and associated SN; the first four bursts are those most clearly associated with a SN event, the following three are those GRBs with firm estimates of $E_{p,i}$ and evidence of SN features in the spectrum of the late-time optical afterglow. *Lower panel*: events with deep limits to the magnitude of a possible associated SN. The values of $E_{p,i}$ and E_{iso} are taken from Amati (2006), except for GRB 060218, GRB 040701, GRB 060505 and GRB 060614 (see text); those of θ_{jet} and E_{jet} are taken from Nava et al. (2006) and Friedman & Bloom (2005), except for GRB 060218 (Soderberg et al. 2006b; Fan et al. 2006) and GRB 060614 (Della Valle et al. 2006). The $E_{p,i}$ upper limit for GRB 031203 is based on the value by Ulanov et al. (2005) combined with the evidence of a soft X-ray excess inferred from the dust echo measured by XMM-*Newton* (see text). References for SN properties are given in the last column. The peak V-band magnitude M_V of SN 2005nc was derived after assuming $(B - V) \sim 0.5$; M_V of SN 2002lt was derived after assuming $(U - V)_{max} \sim 0.2$, as observed for SN 1994I (Richmond et al. 1996).

GRB/SN	z	$E_{p,i}$ (keV)	E_{prompt}^{iso} (10^{50} erg)	θ_{jet} (deg)	E_{prompt}^{jet} (10^{50} erg)	SN $E_K^{iso\,a}$ (10^{50} erg)	SN peak mag	Ref.[b]
980425/SN 1998bw	0.0085	55 ± 21	0.01 ± 0.002	–	<0.012	200–500	$M_V = -19.2 \pm 0.1$	(1, 2, 3, 4)
060218/SN 2006aj	0.033	4.9 ± 0.3	0.62 ± 0.03	>57	0.05–0.65	20–40	$M_V = -18.8 \pm 0.1$	(5, 6)
031203/SN 2003lw	0.105	<200	1.0 ± 0.4	–	<1.4	500–700	$M_V = -19.5 \pm 0.3$	(3, 7)
030329/SN 2003dh	0.17	100 ± 23	170 ± 30	5.7 ± 0.5	0.80 ± 0.16	~400	$M_V = -19.1 \pm 0.2$	(3, 8)
020903/BL-SNIb/c	0.25	3.4 ± 1.8	0.28 ± 0.07	–	<0.35	–	$M_V \sim -18.9$	(9)
050525A/SN 2005nc	0.606	127 ± 10	339 ± 17	4.0 ± 0.8	0.57 ± 0.23	–.	$M_V = -19.4_{-0.5}^{+0.1}$	(10)
021211/SN 2002lt	1.01	127 ± 52	130 ± 15	8.8 ± 1.3	1.07 ± 0.13	–	$M_V \sim -19 \pm 1$	(11)
060505	0.089	>160	0.3 ± 0.1	–	–	–	$M_V > -13.5$	(12)
060614	0.125	10–100	25 ± 10	~12	0.45 ± 0.20	–	$M_V > \sim -13$	(12, 13, 14)
040701	0.215	<6.	0.8 ± 0.2	–	–	–	$M_V > -16$	(9)

[a] Values derived by modeling optical data of the SN component with hypernova models, like, e.g., the 1-dimensional synthesis code by Mazzali et al. (2006a).
[b] References: (1) Mazzali et al. (2001), (2) Maeda et al. (2006), (3) Mazzali et al. (2006a) and references therein, (4) Galama et al. (1998), (5) Mazzali et al. (2006b), (6) Pian et al. (2006), (7) Malesani et al. (2004), (8) Hjorth et al. (2003), (9) Soderberg et al. (2005), (10) Della Valle et al. (2006a), (11) Della Valle et al. 2003, (12) Gal-Yam et al. (2006), (13) Della Valle et al. (2006b), (14) Fynbo et al. (2006).

(Price et al. 2006; Fugazza et al. 2006). GRB 060614 is a very important event, because the upper limit to the luminosity of the SN possibly associated with it was at least two orders of magnitude fainter (Della Valle et al. 2006b; Fynbo et al. 2006; Gal-Yam et al. 2006) than the peak luminosity of broad-lined SNe-Ibc normally associated with GRBs (see Table 1). In order to analyze the location of GRB 060614 in the $E_{p,i} - E_{iso}$ plane, we performed estimates of $E_{p,i}$ and E_{iso} based on the spectra and fluences of two portions of the event measured by Konus-Wind in 20 keV–2 MeV energy range. Golenetskii et al. (2006) report E_p of 302_{-85}^{+214} keV for the first bright pulse lasting ~8.5 s and providing ~20% of the total fluence. The Konus-Wind spectrum of the subsequent part of the event, composed by softer pulses, can be fitted by a simple power-law with photon index of ~2.13 ± 0.05, indicating that E_p may be close or below the 20 keV low energy bound. In order to estimate a reasonable $E_{p,i}$ range for the average spectrum, we performed both a weighted average of the E_p measured in the two time intervals (by assuming E_p 10 or 20 keV for the second interval) and simulations (i.e. we generated fake spectra of the two intervals, summed them and fit them with the Band function). We find that $E_{p,i}$ of GRB 060614 likely lies in the range 10–100 keV, which is also consistent with the average photon index of ~2 measured by Swift/BAT in 15–150 keV (Barthelmy et al. 2006; Gehrels et al. 2006). As can be seen in Fig. 1, GRB 060614 is consistent with the $E_{p,i} - E_{iso}$ correlation as most GRB/SN events, therefore suggesting that the position in the $E_{p,i} - E_{iso}$ plane of long GRBs does not critically depend on the progenitors properties.

In the second part of Table 1, we also report the $E_{p,i}$ and E_{iso} values, or upper/lower limits, for other two long GRBs/XRFs with deep limits to the magnitude of a possible associated SN, XRF 040701 (Soderberg et al. 2005) and GRB 060505 (Fynbo et al. 2006). For these two events, no estimates of E_p are available and we could estimate only approximate upper/lower limits based on the available published information. In the case of XRF 040701, E_{iso} and the upper limit to $E_{p,i}$ were inferred based on the HETE–2 spectral information reported by Barraud et al. (2004), who quote an average photon index of 2.4 ± 0.3. This indicates that the peak energy of XRF 040701 is likely towards, or below, the low bound of the WXM + FREGATE 2–400 keV energy band. We conservatively assumed $E_p < 5$ keV, which, by assuming the redshift of 0.215, translates in an upper limit to $E_{p,i}$ of ~6 keV. The E_{iso} range was computed by assuming a Band spectral shape with $\alpha = -1.5$, $\beta = -2.4$ and $E_p = 1$–5 keV, normalized to the measured 2–30 keV fluence. Poor spectral information is available for GRB 060505; based on Swift/BAT data, Hullinger et al. (2006) report a photon index of 1.3 ± 0.3 in the 15–150 keV energy range. Thus, for this event E_p is likely above 150 keV; E_{iso} was computed by assuming a Band spectral shape with $\alpha = -1.3$, $\beta = -2.5$ and $E_p = 150$–1000 keV, normalized to the measured 15–150 keV fluence. Finally, the VLT afterglow light curve of GRB 060614 shows a break which, if interpreted as due to collimated emission, gives a jet angle of ~12 deg (Della Valle et al. 2006b) and a collimation corrected radiated energy E_{jet} of $4.5 \pm 2.0 \times 10^{49}$ erg, consistent with the $E_{p,i} - E_\gamma$ correlation (Ghirlanda et al. 2004).

3. Discussion

3.1. GRB 060218: existence of truly sub-energetic GRBs

The fact that the two closest, sub-energetic, and SN–associated GRBs, 980425 and 031203, are outliers of the $E_{p,i} - E_{iso}$ correlation stimulated several works also in the framework of GRB/SN unification models. The most common interpretation is that they were "standard" GRBs viewed off-axis (e.g., Yamazaki et al. 2003; Ramirez-Ruiz et al. 2005). These scenarios explain both the low value of E_{iso} and the deviation from the $E_{p,i} - E_{iso}$ correlation by means of relativistic Doppler and beaming effects. For instance (e.g., Yamazaki et al. 2003), by assuming a uniform jet and a viewing angle, θ_v, larger than the jet opening angle, θ_{jet}, it is found that $E_{p,i} \propto \delta$ and $E_{iso} \propto \delta^{1-\alpha}$, where α is the average power-law index of the prompt emission photon spectrum in the hard X-ray energy band (typically between -1 and -2) and δ

is the relativistic Doppler factor $\delta = \{\Gamma[1 - \beta \cos(\theta_v - \theta_{jet})]\}^{-1}$ (Γ is the bulk Lorentz factor of the plasma and β is the velocity of the outflow in units of speed of light), which decreases as θ_v increases. For large off-axis viewing angles the different dependence of $E_{p,i}$ and E_{iso} on δ would cause significant deviations from the $E_{p,i} - E_{iso}$ correlation and a very low *observed* value of E_{iso}. Off-axis scenarios make also predictions on the multi-wavelength afterglow light curve. At the beginning, when the Lorentz factor of the relativistic shell, Γ, is very high, the flux detected by the observer is much weaker with respect to the case $\theta_v < \theta_{jet}$. As Γ decreases, and thus the beaming angle (which is proportional to $1/\Gamma$) increases, the observer measures a slow rise, or a flat light curve in case the GRB is structured (e.g. Granot et al. 2002; Rossi et al. 2002). The light curves show a peak or a smooth break when $1/\Gamma \sim \theta_v$, and then behave in the same way as for an on-axis observer. This peak, or break, is due to a purely geometrical factor, thus it should be "achromatic", i.e. occur at the same times at all wavelengths. While theoretical modeling shows that the nebular spectrum of SN1998bw, associated with GRB 980425, is consistent with an aspherical explosion seen off-axis (Maeda et al. 2006), radio-observations (Berger et al. 2003a) seem to exclude the detection of relativistic off-axis ejecta, because of the lack of the detection of the late (a few years at most) radio re-brightening predicted by off-axis models (see also Ramirez-Ruiz et al. 2005). However, it was suggested that the still low radio flux may be still consistent with the off-axis interpretation if the density of the circum-burst wind is at least 1 order of magnitude lower than expected (e.g., Waxman 2004).

In light of the above arguments, the consistency of GRB 060218 with the $E_{p,i} - E_{iso}$ correlation, as presented in Fig. 1 and discussed in Sect. 2, suggests that this event, the most similar to GRB 980425 because of its very low E_{iso}, very low z and prominent association with a SN (2006aj), was not seen off-axis. This conclusion is further supported by its multi-wavelength afterglow properties. The early-time ($t \lesssim 0.5$ d) light curves of GRB 060218 exhibited a slow rise, as observed in the optical/UV, X-ray and soft gamma-ray bands (Campana et al. 2006). However, the peak time was dependent upon the frequency, occurring earlier at shorter wavelengths, contrary to the expectations for an off-axis jet (e.g. Granot et al. 2002). Another piece of evidence comes from radio data: the radio afterglow light curves can be fitted with standard GRB afterglow models (i.e. without the need to involve viewing angle effects), as shown by Soderberg et al. (2006) and Fan et al. (2006).

Finally, as is shown in Fig. 2, we find that GRB 060218 and the other sub-energetic events GRB 980425 and GRB 031203 follow and extend the correlation between E_{iso} and the X-ray afterglow $2-10$ keV luminosity at 10 h from the event reported by De Pasquale et al. (2006) and Nousek et al. (2006). For the events in the sample of Nousek et al. (2006) the $2-10$ keV $L_{X,10}$ values were computed from the $0.3-10$ keV values by assuming a typical X-ray afterglow photon index of 2. The $1-10\,000$ keV E_{iso} values are taken from Amati (2006); for those few events not included in the sample of Amati (2006), we derived the $1-10\,000$ keV E_{iso} from the $10-500$ keV value reported by Nousek et al. (2006) by assuming a Band spectral shape (Band et al. 1993) with $\alpha = -1$, $\beta = -2.3$ and $E_0 = 15$ keV, for those events with $15-150$ keV photon index > 2, or $E_0 = 200$ keV, for those events with photon index < 2. The X-ray luminosities for GRB 980425, GRB 031203 and GRB 060218 were derived from the X-ray afterglow light curves reported by Pian et al. (2000), Watson et al. (2006) and Campana et al. (2006), respectively. Figure 2 clearly shows that these 3 events are sub-energetic also
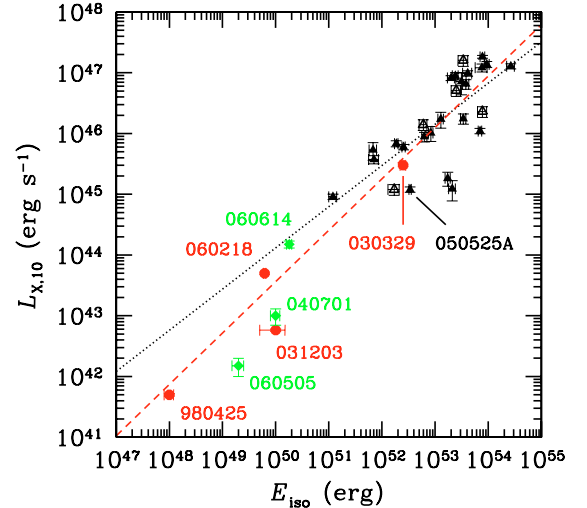

Fig. 2. $2-10$ keV afterglow luminosity at 10 h $L_{X,10}$ vs. E_{iso} for the events included in the sample of Nousek et al. (2006; triangles) plus the 3 sub-energetic GRB 980425, GRB 031203, GRB 060218, the other GRB/SN event GRB 030329 (circles), and 3 GRBs with known z and deep limits to the peak magnitude of associated SN, XRF 040701, GRB 060505 and GRB 060614 (diamonds). Empty triangles indicate those GRBs for which the $1-10\,000$ keV E_{iso} was computed based on the $100-500$ keV E_{iso} reported by Nousek et al. (2006) by assuming an average spectrum (see text). The plotted lines are the best fit power-laws obtained without (dotted) and with (dashed) sub-energetic GRBs and GRB 030329.

from the point of view of their X-ray afterglow emission. While the correlation based on "normal" events was found to be only marginally significant (De Pasquale et al. 2006; Nousek et al. 2006), here we show that after including sub-energetic GRBs, it becomes highly significant (chance probability $\sim 10^{-11}$). This result further indicates that sub-energetic GRBs may be intrinsically weak and belong to an extension of the normal cosmological events. Also, qualitatively, in the off-axis viewing scenarios, one would expect that, due to the rapidly decreasing Lorentz factor of the fireball, and thus to the rapidly increasing beaming angle, the prompt emission should be much more depressed with respect to afterglow emission at ~ 10 h. This would imply that the points corresponding to the three sub-energetic events should lie above the extrapolation of the law best fitting on-axis GRBs, which is not the case.

All the above evidences indicate that the local underluminous GRB 060218 was not seen off-axis and point towards the existence of a class of truly sub-energetic GRBs.

3.2. Implications for GRBs occurrence rate

Several authors (e.g., Guetta et al. 2004; Della Valle 2006; Pian et al. 2006; Soderberg et al. 2006b; Cobb et al. 2006) have pointed out that sub-energetic GRBs may be the most frequent gamma-ray events in the Universe. Indeed, since the volume sampled at $z = 0.033$ is $10^4 \div 10^6$ times smaller than that probed by classical, distant GRBs, the fact that we have observed one sub-energetic event out of ~ 80 GRBs, with estimated redshift, indicates that the rate of these events could be as large as ~ 2000 GRBs Gpc^{-3} yr^{-1} (e.g. Guetta & Della Valle 2006; Liang et al. 2006; Soderberg et al. 2006b). The hypothesis of such high rate is further supported by the possibility, investigated by Ghisellini et al. (2006), that also GRB 980425 and GRB 031203 may be truly sub-energetic events.
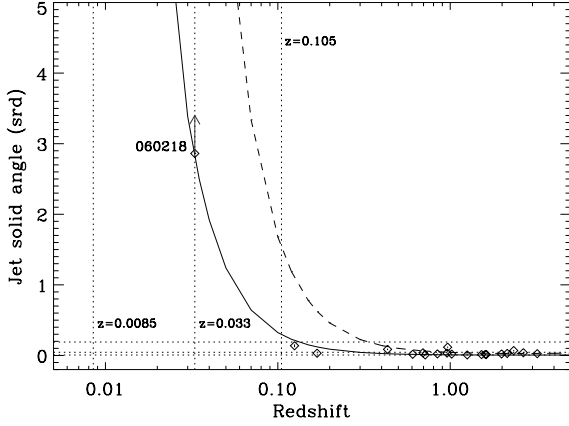
Fig. 3. GRBs jet solid angles as a function of redshift. Values are taken from Nava et al. (2006), except for GRB 060218 and GRB 060614 (see text). The solid and dashed lines show, as a function of redshift, the jet solid angle required to have a constant detection rate as a function of redshift by assuming a homogeneous source distribution in time and space, a flat luminosity function and neglecting detector's sensitivity threshold. The solid line is normalized to the detection probability of a GRB with redshift and solid angle of GRB 060218; the dashed line to the detection probability of a GRB lying at $z = 1$ and with jet solid angle of 7°. The three vertical dotted lines correspond to the redshifts of GRB 980425, GRB 060218 and GRB 031203. The horizontal lines delimitate the range of jet opening angles found for cosmological GRBs. See text for details.

However in these estimates, particular attention has to be paid to the collimation angle of the emission. Indeed from radio afterglow modeling and no detection of the jet break, it has been inferred that GRB 060218 was much less collimated than normal cosmological GRBs (see Sect. 2). This suggests that local sub-energetic GRBs are much less collimated than the brighter and more distant ones. In this case, the larger jet solid angle would, at least partly, compensate the smaller co-moving volume, thus making the occurring rate of sub-energetic GRBs consistent with, or not much higher than, that of bright cosmological GRBs (see Guetta & Della Valle 2006). However, by considering the combined effect of the co-moving volume and jet opening angle on the detection probability, it can be seen that the detection of local and quasi spherical GRBs like GRB 060218 is consistent with the hypothesis that the jet angle distribution of local and distant GRBs is the same. Indeed, by neglecting detector's limiting sensitivity and by assuming a uniform jet, a homogeneous distribution in space, a rate independent of redshift, and a flat luminosity function, the probability of detecting a GRB lying at a redshift z and emitting within a solid angle Ω is

$$\frac{dP(z,\Omega)}{dz} \propto \frac{\Omega}{4\pi} \times 4\pi \frac{dV_c}{dz} \propto \Omega \times \frac{dV_c}{dz}$$

where dV_c is the co-moving volume element corresponding to the redshift interval $(z, z + dz)$ (e.g., Weinberg 1972; Peebles 1993). The term $\Omega/4\pi$ accounts for the fact that the detection probability increases with increasing jet opening angle, and the term $4\pi dV_c/dz$ for the fact that for an uniform distribution the number of sources within z and $z + dz$, and thus the detection probability (if neglecting detector's sensitivity limit), increases with redshift. This is graphically shown in Fig. 3, where we plot the jet solid angles of GRBs in the sample of Nava et al. (2006) plus GRB 060218 and GRB 060614 (see Sect. 2), as a function of redshift. As can be seen, no trend in the jet angle distribution is apparent down to $z \sim 0.1-0.2$, whereas there is a sudden

increase in the jet opening angle for very low redshift if we include the lower limit to the collimation angle of GRB 060218. The solid and dashed lines show, as a function of redshift, the jet solid angle that a GRB must have in order to maintain constant $P(z, \Omega)$. The solid line is normalized to the redshift and jet angle lower limit of GRB 060218, while the dashed line is normalized to the detection probability of a GRB with jet opening angle of 7° and located at a redshift of 1. Sources lying on the right line have a detection probability ~5 times higher than those lying on the left one. For instance, at the redshift of GRB 060218 a very weakly collimated emission is needed in order to have the same detection probability of a source with jet angle ~10° located at $z \sim 0.2-0.3$ (solid line), but even a spherical emission has ~4 times lower detection probability of a source with a jet angle ~5−10 degrees located at a redshift of ~1−2. At the redshift of GRB 980425 the detection probability is very low, compared to that of cosmological GRBs, even for spherical emission. Of course, things change if we include the possibility of detecting a source even when it is seen off-axis, which could be the case for GRB 980425 and GRB 031203 (as discussed above). Thus, the very low redshift and (likely) wide jet opening angle of GRB 060218, and also the possible off-axis detection of GRB 980425, are consistent with the hypothesis that local GRBs have a jet angle distribution similar to that of distant GRBs. A possible caveat with this scenario is the lack of detection of bright weakly collimated GRBs both in the local and high redshift universe. The most straightforward explanation is that there is a correlation between E_{iso} and jet opening angle, as it may be suggested by the narrow distribution of collimation corrected energies (Frail et al. 2001; Berger et al. 2003b; Ghirlanda et al. 2004). In this case, we would miss both close bright GRBs, because their narrow jet opening angle make their detection very unlikely (Fig. 3), and high redshift weakly collimated events, because they are the weaker ones and thus, due to the detectors sensitivity limits (not considered in Fig. 3), their detection probability quickly decreases with increasing redshift.

The main consequence of this scenario is that the occurrence rate of GRBs may be really as high as ~2000 GRBs Gpc^{-3} yr^{-1}, both in the local Universe and at high redshift.

3.3. The $E_{p,i} - E_{iso}$ plane and the GRB/SN connection

From Fig. 1, one derives that all GRBs associated with SNe are consistent, or potentially consistent, with the $E_{p,i} - E_{iso}$ correlation independently of their E_{iso} or the SN peak magnitude and kinetic energy, with the exceptions of GRB 980425 and possibly GRB 031203. However, for these two events, and in particular for GRB 980425, given its very low redshift, the possibility that the deviation from the $E_{p,i} - E_{iso}$ correlation is not real but due to an off-axis viewing angle cannot be excluded. Ghisellini et al. (2006) have proposed alternative explanations for the peculiar behavior in the $E_{p,i} - E_{iso}$ plane of these two events. One is the presence of scattering material of large optical depth along the line of sight (which would have the effect of decreasing the apparent E_{iso} and increasing the apparent $E_{p,i}$). As an alternative, they suggest that, due to the limited energy band of the instruments which detected them, the softest component of the prompt emission of these two events was missed, leading to an overestimate of $E_{p,i}$. The latter explanation is also supported by the fact that, without the XRT (0.2−10 keV) measurement, the peak energy of GRB 060218 would have been overestimated and this burst would have been classified as another outlier to the $E_{p,i} - E_{iso}$ correlation. Also, for GRB 031203 there is possible evidence from the X-ray dust echo measured by XMM
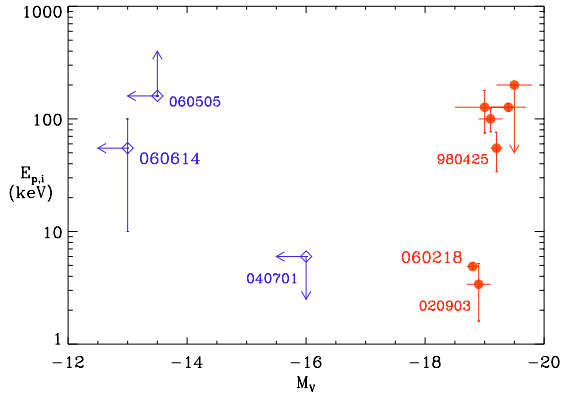
Fig. 4. Peak energy of GRB prompt emission vs. SN peak magnitude. Data are taken from Table 1. Diamonds represent GRBs with upper limits to the luminosity of the possible associated SN. Filled circles are GRBs with associated SNe.

(Vaughan et al. 2004; Watson et al. 2006) that the soft prompt emission component was missed by INTEGRAL/ISGRI, operating at energies above ~10−15 keV. All these scenarios support the hypothesis that the true $E_{p,i}$ and E_{iso} of GRB 980425 and GRB 031203 are consistent with the $E_{p,i} - E_{iso}$ correlation, as all the other GRB/SN events. However, one must caution that both the inference that the $E_{p,i}$ of GRB 980425 could have been as low as <1 keV (required to fit the $E_{p,i} - E_{iso}$ correlation) and the estimate of the prompt soft X-ray flux of GRB 031203 based on the dust echo are strongly model dependent.

The "optical" properties (i.e. luminosity at peak and expansion velocities) of the SNe listed in Table 1 vary by a factor ~5−10 at most, while the gamma-ray budget covers about 4 orders of magnitude. This fact suggests that the difference between sub-energetic and bright GRBs should not depend on the properties of SN explosions, which are similar, but it is likely related to the efficiency with which SNe are able to convert a significant fraction of their kinetic energy into relativistic ejecta. However, after correcting E_{iso} for the jet opening angle inferred from the break time in the optical afterglow light curve, it is found that the GRB/SN events GRB 030329, GRB 021211 and GRB 050525A are characterized by radiated energies, E_{jet}, in the range $(\sim 0.5-1) \times 10^{50}$ erg (see Table 1), showing that also for cosmological GRB/SN events the energy radiated in gamma-rays may be only a small fraction of the SN kinetic energy ($\sim 10^{51}-10^{52}$ erg). The location of GRB/SN events in the $L_{X,10} - E_{p,i} - E_{iso}$ plane (Fig. 2) further supports the hypothesis that the emission mechanisms at play are independent of the SN properties.

No significant correlations are found among the quantities reported in Table 1. As can be seen in Fig. 4, no evidence of the correlation between the peak magnitude of the SN and the $E_{p,i}$ of the associated GRB reported by Li (2006) is apparent in our enlarged sample. Even considering only the 7 GRBs associated with bright SNe (filled circles), small variations of M_V correspond to variations of $E_{p,i}$ by a factor up to ~100. Thus, given also the scanty statistics, the existence of this correlation cannot be currently supported.

3.4. GRB 060614: a different progenitor but similar emission mechanisms ?

We find that the long lasting GRB 060614, for which an association with a bright supernova can be excluded (Della Valle et al. 2006b; Fynbo et al. 2006; Gal-Yam et al. 2006), is also consistent

with the $E_{p,i} - E_{iso}$ correlation (see Fig. 1). On the other hand, Gehrels et al. (2006) have shown that, despite GRB 060614 lasted more than 100 s, it lies in the same region of the temporal lag – peak luminosity plane populated by short GRBs. This evidence may point to the existence of a class of GRBs with common properties and similar progenitors, independently on their duration. The fact that GRB 060614 follows the $E_{p,i} - E_{iso}$ correlation, while short events do not, is a challenging evidence for this hypothesis (unless, as discussed by Gehrels et al. 2006, one considers only the first pulse of this event, which is characterized by values of $E_{p,i}$ and E_{iso} inconsistent with the correlation).

The inconsistency of short GRBs with the $E_{p,i} - E_{iso}$ correlation may be explained, for instance, with the relevant role of the circum-burst environment density and distribution, which are expected to be very different in the merger scenario (short GRBs) with respect to the collapse scenario (long GRBs). The fact that both long GRBs associated with SN and long GRBs without SN are consistent with the $E_{p,i} - E_{iso}$ correlation may suggest that the circum-burst environment, the energy injection, or other physical mechanisms at play are similar for the their progenitors. This hypothesis is further supported by: i) the location of GRB 060614 and XRF 040701 in the $E_{iso} - L_{X,10}$ plane, which is consistent (Fig. 2) with those of GRB/SN events (data for XRF 040701 and GRB 060614 were derived from Fox et al. 2004 and Mangano et al., paper in preparation, respectively); ii) the fact that the existence of long lasting GRBs associated with very weak SNe may still be explained with the explosion of massive progenitor stars (see Della Valle et al. 2006; Tominaga et al. 2007, in preparation) similarly to "classical" long-duration GRBs (e.g., Woosley & Bloom 2006).

3.5. GRB 060505

Very deep upper limits to the luminosity of an associated SN have also been found for GRB 060505 (Fynbo et al. 2006). Differently from GRB 060614 and XRF 040701, this event is inconsistent with the $E_{p,i} - E_{iso}$ correlation. One (unlikely) explanation for this behavior could be that the association of this event with a galaxy at $z = 0.089$ is not physical but due to chance superposition. We computed the track of GRB 060505 in the $E_{p,i} - E_{iso}$ plane as a function of redshift (see dotted curve in Fig. 2) and find that it is always outside the $\pm 2\sigma$ confidence region and that it would be marginally consistent (i.e. within 99% c.l.) with the $E_{p,i} - E_{iso}$ correlation for $\sim 2 < z < 6$. It must be cautioned that the spectral information provided by Swift/BAT for this event are rather poor and based on survey mode data collected only up to 60 s after the GRB onset, because Swift was approaching the South Atlantic Anomaly. In addition, the short duration of this event, 4 ± 1 s, combined with its low fluence and hard spectrum (Hullinger et al. 2006) may indicate that it belongs to the short GRB class, as also discussed by Fynbo et al. (2006). In this case the inconsistency with the $E_{p,i} - E_{iso}$ correlation (which is not followed by short GRBs) is not surprising.

4. Conclusions

We analyzed and discussed the location in the $E_{p,i} - E_{iso}$ plane of two very interesting long GRBs: the local, sub-energetic GRB 060218, associated with SN 2006aj, and GRB 060614, for which an association with a bright SN similar to other GRB-SNe can be excluded. We included in our analysis also other GRB/SN events and two more GRBs with very deep limits to the magnitude of an associated SN. The main implications of our analysis can be summarized as follows.

a) The consistency of GRB 060218 with the $E_{p,i} - E_{iso}$ correlation favors the hypothesis that this is a truly sub-energetic event rather than a GRB seen off axis. The ratio between E_{iso} and $L_{X,10}$ and the radio afterglow properties of this event further support this conclusion. If this is the case, GRB 060218 can be considered as the prototype of a local sub-energetic GRB class.

b) Based on simple considerations on co-moving volume and jet solid angle effects on GRB detection probability as a function of redshift, it is found that the detection of a close, weak and poorly collimated (as suggested by modeling of radio data) event like GRB 060218 is consistent with the hypothesis that the rate and jet opening angle distributions of local GRBs are similar to those of cosmological GRBs. A correlation between jet opening angle and luminosity can explain the lack of detection of local bright GRBs and of distant, weakly collimated events. If this is the case, the occurrence rate of GRBs may be as high as ~2000 GRBs Gpc^{-3} yr^{-1}, both in the local Universe and at high redshift.

c) All GRB/SN events are consistent with the $E_{p,i} - E_{iso}$ correlation, except for GRB 980425 and GRB 031203. However, the first event is so close that an off-axis detection is possible, whereas for the latter there are observational indications that the $E_{p,i}$ value could be consistent with the correlation. The consistency of GRB/SN events with the $E_{p,i} - E_{iso}$ correlation, combined with energy budget considerations and their location in the $E_{iso} - L_{X,10}$ diagram, show that the emission properties of long GRBs do not depend on the properties of the associated SN. No clear evidence of correlation is found between GRB and SN properties. in particular, all GRB/SN events seem to cluster in the $E_{p,i}$ – SN peak magnitude plane, with the only exception of GRB 060218.

d) The consistency of GRB 060614 with the $E_{p,i} - E_{iso}$ correlation shows that the emission mechanisms at play in long GRBs may be independent from the progenitor type. GRB 060505, another GRB with stringent upper limits to the luminosity of an associated SN, is inconsistent with the $E_{p,i} - E_{iso}$ correlation. However, the short duration, low fluence and hard spectrum of this event may suggest that it belongs to the short GRBs class.

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