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An upper limit to the energy of gamma-ray bursts indicates that GRB/SNe are powered by magnetars

P. A. Mazzali^{1,2,3*}, A.I. McFadyen⁴, S.E. Woosley⁵, E. Pian⁶, M. Tanaka⁷

¹*Astrophysics Research Institute, Liverpool John Moores University, 146 Brownlow Hill, Liverpool L3 5RF, UK*

²*INAF-Osservatorio Astronomico, vicolo dell'Osservatorio, 5, I-35122 Padova, Italy*

³*Max-Planck Institut für Astrophysik, Karl-Schwarzschildstr. 1, D-85748 Garching, Germany*

⁴*Physics Dept., New York University, New York, NY, USA*

⁵*Astronomy Dept., University of California, Santa Cruz, Santa Cruz, Ca, USA*

⁶*INAF IASF, Via P. Gobetti 101, I-40129 Bologna, Italy*

⁷*National Astronomical Observatory of Japan, Mitaka, Tokyo, Japan*

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ABSTRACT

The kinetic energy of supernovae (SNe) accompanied by gamma-ray bursts (GRBs) tends to cluster near 10^{52} erg, with 2×10^{52} erg an upper limit to which no compelling exceptions are found (assuming a certain degree of asphericity), and it is always significantly larger than the intrinsic energy of the GRB themselves (corrected for jet collimation). This energy is strikingly similar to the maximum rotational energy of a neutron star rotating with period 1 ms. It is therefore proposed that all GRBs associated with luminous SNe are produced by magnetars. GRBs that result from black hole formation (collapsars) may not produce luminous SNe. X-ray Flashes (XRFs), which are associated with less energetic SNe, are produced by neutron stars with weaker magnetic field or lower spin.

Key words: Supernovae: general – stars: magnetars – gamma-ray bursts: general

1 INTRODUCTION

The connection between long-duration Gamma-Ray Bursts (GRBs) and SNe is well established in the local Universe. Following the first cases of coincidences (Galama et al. 1998; Stanek et al. 2003; Hjorth et al. 2003; Matheson et al. 2003; Malesani et al. 2004; Gal-Yam et al. 2004; Thomsen et al. 2004), now for almost every GRB at redshift $z \lesssim 0.3$ a corresponding SN has been identified (Woosley & Bloom 2006; Pian et al. 2006; Mirabal et al. 2006; Modjaz et al. 2006; Chornock et al. 2010; Cano et al. 2011a; Bufano et al. 2012; Olivares et al. 2012; Melandri et al. 2012; Xu et al. 2013; Melandri et al. 2014). Despite the diverse properties of their associated GRBs, all GRB/SNe observed so far are luminous, broad-lined Type Ic SNe (no H, no He, Filippenko 1997). The very broad lines indicate a high expansion velocity of the ejecta, and point to a high explosion kinetic energy (E_k) (Mazzali et al. 2000).

Detailed models of GRB/SNe yield a typical SN E_k of a few 10^{52} erg (depending on the asphericity of the SN), an ejected mass $M_{ej} \sim 10M_\odot$, and a ^{56}Ni mass of $\sim 0.4M_\odot$. This places GRB/SNe at the luminous, ener-

getic and massive end of SNeIc (e.g. Mazzali et al. 2013) and points to a massive star origin (e.g. Mazzali et al. 2006a). Two recent events confirm and reinforce this trend: SN 2013cq/GRB130427A (Maselli et al. 2014) and SN2013dx/GRB130702A (Singer et al. 2013). Although the two GRBs are very different in energy, the former extremely powerful, similar to cosmological ones, the latter a normal GRB, the SNe are again similar (Melandri et al. 2014, D’Elia et al., in prep.).

It has been proposed that long GRBs are produced by the Collapsar mechanism, where a massive star collapses directly to a black hole (BH). Accretion on the BH releases energy in the form of a relativistic jet which may explode the star and produce a visible SN if ^{56}Ni is synthesised in the dense neutrino wind emanating from the accretion disc (Woosley 1993; MacFadyen & Woosley 1999).

SNeIc associated with X-ray Flashes (XRFs) have a smaller E_k , more similar to ordinary SNeIc, and are not as luminous (Pian et al. 2006; Mazzali et al. 2006b; Bufano et al. 2012). Models indicate progenitor stars of $\sim 20 - 25M_\odot$, which are expected to collapse to Neutron Stars (NS). Their E_k (a few 10^{51} erg) appears to be consistent with energy injection from a magnetar, a rapidly spinning magnetised NS (Mazzali et al. 2006b). This mech-

* E-mail: P.Mazzali@ljmu.ac.uk

anism taps the energy in the magnetic field and may also give rise to a relativistic jet (see e.g., Thompson et al. 2004; Dessart et al. 2008).

Observational and theoretical evidence has been mounting that more massive stars can also collapse to NS (Muno et al. 2006; Ugliano et al. 2012; Sukhbold & Woosley 2014). Magnetar jets and their potential as a source of GRBs have been investigated in various papers, suggesting that magnetar energy can be used to energise GRBs or XRFs (Bucciantini et al. 2007, 2008, 2009; Metzger et al. 2011).

It has also been proposed that very rapidly spinning magnetars can explain the much brighter light curves of GRB/SNe (Uzdensky & MacFadyen 2007). This may conflict with the observation in SN1998bw of strong emission lines of Fe, which indicate a high ^{56}Ni yield (Patat et al. 2001; Mazzali et al. 2001). On the other hand, only SN1998bw could be followed late enough to observe Fe lines.

One of the most interesting unsolved questions in GRB science is what actually drives the event. In the collapsar model the jet generated by the BH explodes the star, but is its energy sufficient to impart a high E_k to the SN? Simulations have so far not tested this, but the energy needed for the jet to emerge from the star and unbind it ($\sim 3 \times 10^{51}$ erg, Lazzati et al. 2013) appears to be much smaller than the SN E_k . In the magnetar scenario, if the coupling is large energy may be extracted from the NS and added to the SN E_k , which would otherwise derive from the classical neutrino mechanism. The sub-relativistic outflow may not be highly collimated, as indicated by the distribution of SN material (Mazzali et al. 2006b, 2007). In this scenario energy production would be limited by the NS spin rate.

We analyse the global properties of the GRBs and their SNe in order to look for indications of a preferred mechanism. We compare the energies of GRBs, XRFs, and their accompanying SNe. In Section 2.1 we estimate the intrinsic energy of low-redshift GRBs ($z \lesssim 0.35$) with associated SNe by applying a correction for the jet opening angle to the observed γ -ray energies. In Section 2.2 we estimate the energy in relativistic ejecta as probed by radio data. In Section 2.3 we compare both of these to the SN E_k as derived from modelling. In Section 3 we present our results. In Section 4 we extend the comparison to all GRBs at higher redshift for which a SN was reported and discuss our findings.

2 NEARBY GRBS, XRFs, AND THEIR SNE

Isotropic-equivalent energies (E_{iso}) of nearby GRBs connected with well-studied SNe are extremely diverse. GRB980425 had a very low E_{iso} , which was one of the aspects that raised doubts on the reality of the first GRB/SN association. On the other hand GRB030329, associated with SN2003dh, was similar to many long GRBs. GRB130427A has $E_{\text{iso}} \sim 10^{54}$ erg, comparable to cosmological GRBs. However, E_{iso} is unlikely to be the real jet energy.

The true energy of the jet, E_γ , can be estimated from E_{iso} , adopting a correction for collimation. Alternatively, radio energy is thought to be a good proxy for the energy of relativistic material, assuming that this energy is completely

used up in the interaction with circumstellar material and radiated isotropically at later times (jet radio calorimetry).

A model-dependent estimate of E_γ can be obtained from the timing of the break in the afterglow light curve. An achromatic break may indicate that the edge of the jet swept past our viewing point. This information is however not always available. Its absence may indicate lack of collimation but also just be due to incomplete data. Once E_{iso} has been corrected for jet collimation, which can be quite uncertain (see e.g. Cenko et al. 2010), it can be compared with the SN E_k and with the radio energies.

2.1 Gamma-ray energies of GRBs

Values of E_{iso} of GRB/SNe are listed in Table 1. If an estimate of the jet opening angle θ_{op} was available in the literature or could be derived from the afterglow multiwavelength light curves (as outlined by Sari et al. 1999), we reported this angle and computed the collimation-corrected energy E_γ .

The optical light curves of GRB130702A steepen at $t_{\text{obs}} = 1.17$ days, and the X-ray light curve is compatible with a steepening at about the same time (Singer et al. 2013). If that is a jet break, the jet opening angle is ~ 14 degrees and $E_\gamma \sim 5 \times 10^{48}$ erg. A SN similar to SN1998bw was indeed detected in coincidence with GRB130702A (D’Elia et al., in prep.). No correction is possible for GRBs 980425 and 031203 or the two XRFs.

2.2 Radio energies

We list GRB/SN energies from radio measurements (E_{radio}) in Table 1. Whenever possible, we took estimates from the literature. For GRB130427A/SN2013cq and GRB130702A/SN2013dx E_{radio} was estimated from the available radio data following Li & Chevalier (1999). In the case of GRB130702A/SN2013dx there may be a significant contribution from the afterglow, because radio measurements were taken only 2 rest-frame days after the explosion. Since it is impossible to disentangle the contribution to the radio emission by the GRB from that of the SN, these values must be regarded as upper limits to the SN energy. No radio observations are available for GRB120422A/SN2012bz.

2.3 Kinetic energies of nearby GRB/SNe

We obtained SN E_k (Table 1) from models or from spectroscopic analogues. In particular, E_k of SNe1998bw, 2003dh and 2003lw are from the re-analysis of Mazzali et al. (2006a). For SN2012bz E_k is taken to be equal to that of SN2003dh based on the similarity of the spectra and the light curve (Melandri et al. 2012); $M(^{56}\text{Ni})$ is only 15% less than for SN2003dh. For SN2013cq we used the E_k estimate of Xu et al. (2013), who find a value similar to that of SN1998bw. This is also supported by the fact that the bolometric light curve maximum of SN2013cq, which was accurately measured with HST (Levan et al. 2013; Melandri et al. 2014), is consistent with that of SN1998bw. For SN2013dx, whose light curve is similar to those of other GRB/SNe (D’Elia et al. 2014, in preparation), we took the average of the E_k of SN2010ah (Mazzali et al.

Table 1. Properties of GRB/SNe at $z \lesssim 0.3$.

GRB/SN	z	T90	E_{iso}	θ_{op}	E_{γ}	SN E_{k}	$M(^{56}\text{Ni})$	E_{radio}	Refs.
1	2	[s]	[10^{50} erg]	[deg]	[10^{50} erg]	[10^{50} erg]	[M_{\odot}]	[10^{50} erg]	10
980425 / 1998bw	0.0085	30	0.010 ± 0.002	180	0.010 ± 0.002	500 ± 50	0.43 ± 0.05	~ 0.2	1-3
030329 / 2003dh	0.1685	23	150 ± 30	6 ± 2	0.23 ± 0.05	400 ± 100	0.4 ± 0.1	2.5 ± 0.8	2,4-7
031203 / 2003lw	0.1055	40	1.0 ± 0.4	180	1.0 ± 0.4	600 ± 100	0.6 ± 0.1	0.17 ± 0.06	1,2,8
060218 / 2006aj	0.0335	2000	0.53 ± 0.03	180	0.53 ± 0.03	20 ± 6	0.20 ± 0.05	0.020 ± 0.006	4,9-11
100316D / 2010bh	0.059	>1300	0.7 ± 0.2	180	0.7 ± 0.2	100 ± 60	0.12 ± 0.02	~ 0.2	12-14
120422A / 2012bz	0.283	5	2.4 ± 0.8	23 ± 7	0.05 ± 0.02	400 ± 100	0.3 ± 0.1	–	15,16
130427A / 2013cq	0.3399	160	8100 ± 800	3 ± 1	4 ± 1	640 ± 70	0.4 ± 0.1	6 ± 2	17-20
130702A / 2013dx	0.145	59	6.5 ± 1.0^a	14 ± 4	0.05 ± 0.02	300 ± 60	0.3 ± 0.1	20 ± 5	21-23

^a The uncertainty on E_{iso} is here amended (L. Amati, priv. comm.)

References: 1. Amati (2006); 2. Mazzali et al. (2006a); 3. Li & Chevalier (1999); 4. Amati et al. (2008); 5. Deng et al. (2005); 6. Berger et al. (2003); 7. Gorosabel et al. (2006); 8. Soderberg et al. (2004); 9. Mazzali et al. (2006b); 10. Pian et al. (2006); 11. Soderberg et al. (2006); 12. Starling et al. (2011); 13. Bufano et al. (2012); 14. Margutti et al. (2013); 15. Melandri et al. (2012); 16. Schulze et al. (2014); 17. Maselli et al. (2014); 18. Melandri et al. (2014); 19. Xu et al. (2013); 20. Perley et al. (2013); 21. Singer et al. (2013); 22. D’Elia et al., in prep.; 23. Amati et al. (2013).

2013) and SN 1998bw based on the spectroscopic similarity. For SN 2006aj E_{k} was obtained through modelling (Mazzali et al. 2006b). For SN 2010bh it was estimated by Bufano et al. (2012).

All these E_{k} assume spherical symmetry. However, we know from the distribution of elements (in particular Fe and O as observed through their nebular emission lines) that at least SN 1998bw was significantly aspherical, and was observed near the direction of most rapid expansion, which is consistent with the detection of the GRB (Mazzali et al. 2001). Therefore, spherically symmetric E_{k} are likely to be overestimated. Using 2D explosion models and 3D radiation transport calculations, Maeda et al. (2002) and Tanaka et al. (2007) found that the real SN E_{k} may be a factor of 2-5 smaller. This correction, which is not shown in Fig. 1, would cause the six GRB/SNe to cluster around $E_{\text{k}} \sim (1 - 2) \times 10^{52}$ erg. The E_{k} of the two XRF/SNe do not require a correction, because there is no evidence for asymmetry in SN 2006aj (Mazzali et al. 2007).

3 RESULTS

We can now compare the various energies.

In Fig. 1a the collimation-corrected GRB energy, E_{γ} , is compared to the SN E_{k} , not corrected for asphericity. GRB E_{iso} values range over 6 orders of magnitude. E_{γ} values still cover 3 orders of magnitude, and are always significantly smaller than any SN E_{k} (the diagonal line is $E_{\text{k}} = E_{\gamma}$). This suggests that the GRB jet is unlikely to be the driving phenomenon behind GRB/SNe, as the SN carries most of the energy, as already noted by Woosley & Bloom (2006).

Fig. 1b shows E_{radio} vs the SN E_{k} . Again, the SN energy is always much larger.

Finally, Fig. 1c shows the E_{radio} v. E_{γ} . The GRB energies estimated from the jet break and from the radio, which rely on different wavebands and on observations taken at completely different times, are in general agreement, but the SN E_{k} are much larger than both. This confirms that

E_{radio} is a good proxy for E_{γ} , but not for either the SN E_{k} or the total energy of the event.

4 DISCUSSION

Well-studied GRB/SNe have a roughly standard energy, $E_{\text{k}} \sim (1-2) \times 10^{52}$ erg, if account is taken for asphericity. XRF/SNe have a smaller E_{k} by about a factor of 10. All SN E_{k} are much larger than all of the GRB/XRF E_{γ} , which seem to be capped at a few 10^{50} erg. This suggests that the GRB/SN phenomenon is driven by the SN, not the GRB jet. This evidence challenges a picture in which the relativistic jet explodes the star. Simulations (Lazzati et al. 2013) have shown that the jet can unbind the star, but it is not clear how the jet can transfer the required large E_{k} to the star once it has escaped without E_{γ} increasing to unreasonably large values. Also, it may be less natural for GRB jets to produce SNe with always the same total E_{k} and the same amount of ^{56}Ni to such a degree (Melandri et al. 2014).

On the other hand, the energetics of GRB/SNe are strikingly similar to the rotational energy of a millisecond magnetar. The rotational energy of a rapidly rotating NS is $E_{\text{rot}} \sim 2 \times 10^{52} (M/1.4M_{\odot}) (R/10\text{km})^2 / (P/1\text{ms})^2$, where M is the NS mass, R its radius and P its spin period. Rotational energy can be tapped by rapid spindown on a GRB timescale if the magnetic field is in the magnetar range ($B \sim 10^{15}$ G; Usov 1992; Duncan & Thompson 1992).

This leads us to propose that in GRB/SNe the exploding star gives birth to a highly magnetized millisecond NS. Deposited magnetar energy can further energize the SN, and $E_{\text{k}} \sim 10^{52}$ erg is a limit to the total intrinsic energy of GRB/SNe. This limit has not been violated by any GRB/SN so far, if they are all aspherical.

Magnetar outflows can be focussed into magnetic jets by interaction with the stellar envelope because hoop stress tends to collimate the flow after it comes into pressure equilibrium with the shocked stellar cavity from which the magnetar formed. The collimated magnetic wind (which is sometimes called a "magnetic tower" and is similar to the colli-

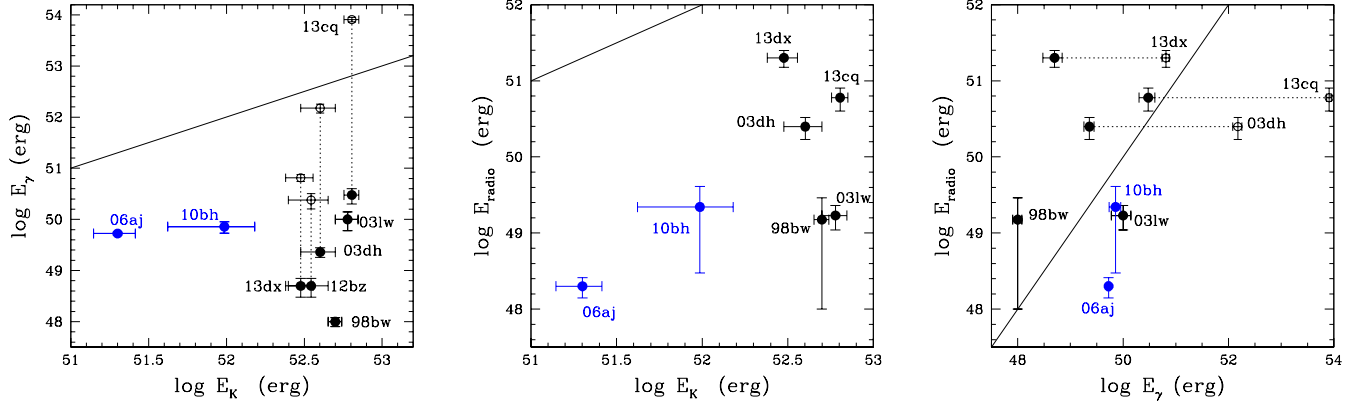


Figure 1. Mutual dependences of the γ -ray energies emitted in the prompt GRB and XRF events, the isotropic kinetic energies of the associated SNe, E_k , and the energies inferred from radio observations E_{radio} . Note that in (a) we have arbitrarily lowered the E_k of SN 2012bz from 4×10^{52} to 3.5×10^{52} erg, to avoid overlap with SN 2003dh. In (a) and (c) when an estimate of the opening angle of the GRB jet exists, isotropic-equivalent energies E_{iso} are shown as open circles, and connected with dashed lines to the corresponding values of the collimation-corrected energies E_γ , shown as filled circles. Black symbols are GRBs and blue symbols are XRFs.

mation of pulsar wind nebulae such as the Crab nebula) can burrow its way out of the star. A very small fraction of the total energy is seen to emerge in the relativistic jet. If a large fraction of the magnetar energy can be transferred to the progenitor star, mostly near the jet axis (Bucciantini et al. 2009), it can be added to the SN energy. The energy deposited also contributes to increasing the isotropic component of the SN E_k (Mazzali et al. 2006b). The SN can take on an increasingly aspherical shape the higher the energy contribution from the magnetar (GRB/SNe are more aspherical than XRF/SNe, Mazzali et al. 2007).

In this scenario, ^{56}Ni may be produced as the expanding magnetar wind shocks the inner star. If this happens quasi-spherically, before the star expands too much, sufficient material can be shocked to produce the several $0.1M_\odot$ of ^{56}Ni in an almost spherical distribution required by GRB/SN light curves (Maeda et al. 2003). The collimated magnetic wind may produce some more ^{56}Ni at high velocities, as also required by the rapid rise of GRB/SN light curves. The late-time deposition of magnetar energy may also contribute to the SN light curve, along with ^{56}Ni . Late-time spectra of more GRB/SNe would be necessary to clarify how much ^{56}Ni is actually produced through the observation of emission lines of Fe. Presently this information is only available for the nearest event, SN 1998bw (Mazzali et al. 2001).

The range of GRB prompt emission energy could be produced by interaction of the jet as it propagates through the stellar envelope. A range of several orders of magnitude in E_γ may be possible, since the jet may be slowed down to variable degrees by the development of instabilities or by interaction with extended outer layers of the star. Small amounts of baryons mixed into the jet can “pollute” it and reduce its γ -ray luminosity. An extended envelope may even block the jet altogether (Mazzali et al. 2008).

Magnetars have been proposed to energise X-ray

Flashes (XRF) and their associated SNeIc (Mazzali et al. 2006b). XRF/SNe have less extreme properties than GRB/SNe, in particular they have smaller E_k (a few 10^{51} erg), luminosities [$M(^{56}\text{Ni}) \sim 0.2M_\odot$, only marginally larger than in ordinary core-collapse SNe], and progenitor masses ($\sim 20M_\odot$, Mazzali et al. 2006b). They are less aspherical than GRB/SNe (Mazzali et al. 2007). They may be the result of lower-spin magnetars.

The progenitors of GRB/SNe are thought to be stars of $M_{\text{ZAMS}} \sim 30\text{--}50M_\odot$. If GRB/SNe are also powered by magnetars then at least some of these stars also collapse to NS.¹ Since GRBs and XRFs exhibit a continuum of properties, this picture reconciles their appearance with their origin as a single mechanism. Indeed, Burrows et al. (2007) find that jets are always produced when a proto-NS is formed, if the magnetic field is very high.

Direct collapse to a BH may not necessarily lead to a luminous SN. The ^{56}Ni produced by the disk wind (MacFadyen & Woosley 1999) could be highly variable and may accrete into the BH, in the spirit of the initial proposal of a “failed SN” (Woosley 1993). This may be the case of the 2 low-redshift GRBs, 060614 and 060505, which showed no SN down to $M(^{56}\text{Ni}) \sim 0.01M_\odot$ (Della Valle et al. 2006; Fynbo et al. 2006; Gal-Yam et al. 2006; Ofek et al. 2007). fallback of ^{56}Ni onto the BH is one possibility (Moriya et al. 2010). On the other hand, both of these GRBs have E_γ well below the magnetar limit.

Magnetars have also been proposed as the energy source for GRBs (Thompson et al. 2004), for GRB/SNe and lu-

¹ Since estimates of the mass of GRB/SN progenitors (e.g. Mazzali et al. 2013) are based on removing a BH remnant of typically $3M_\odot$, if the remnant is a NS instead masses may have to be revised downwards slightly.

minous SNeIb/c (Kasen & Bildsten 2010; Woosley 2010) and for the peculiar SNIb 2005bf (Maeda et al. 2007). Lü & Zhang (2014) find that most GRBs are compatible with being energised by a magnetar. On the other hand, Cenko et al. (2010) find that the energetics of three out of five well-observed high-redshift Swift GRBs have energies similar to the maximum energy provided by a spinning NS (10^{52} erg) even after correction for collimation. Only one of these, GRB080319B, may show a bump in its light curve, but any SN would be very faint (Tanvir et al. 2010). These may indeed all be collapsars.

We checked all other GRBs, at any redshift, for which a SN was reported. Their E_{iso} almost ever exceeds a few 10^{52} erg. Five (991208, 000911, 011121, 020405, 090618) have $E_{\text{iso}} \sim 10^{53} - 10^{54}$ erg (Amati et al. 2008; Baumgartner et al. 2009), but in four of these the optical afterglows exhibit potential jet breaks, leading to substantial energy collimation corrections (Castro-Tirado et al. 2001; Greiner et al. 2003; Price et al. 2003; Cano et al. 2011a). No breaks are reported in the optical afterglow of GRB000911 (Lazzati et al. 2001; Masetti et al. 2005), but the light curve could admit a break at $t \sim 5$ rest-frame days, leading to an energy collimation correction factor of at least 100. For GRB111211 (Lazzarotto et al. 2011; de Ugarte Postigo et al. 2012), no γ -ray energy or fluence is available. From the GRB peak flux (1.5×10^{-6} ergs $^{-1}$ cm $^{-2}$ in 20-60 keV), duration (15 s) and redshift ($z = 0.478$, Vergani et al. 2011) we estimate $E_{\text{iso}} \lesssim 10^{52}$ erg. All these events may be driven by magnetars.

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