A search for *Fermi* bursts associated with supernovae and their frequency of occurrence

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ABSTRACT

Context. Observations suggest that most long duration gamma-ray bursts (GRBs) are connected with broad-line supernovae Ib/c, (SNe-Ibc). The presence of GRB-SNe is revealed by rebrightenings emerging from the optical GRB afterglow 10–15 days, in the rest-frame of the source, after the prompt GRB emission.

Aims. *Fermi*/GBM has a field of view (FoV) about 6.5 times larger than the FoV of *Swift*, therefore we expect that a number of GRB-SN connections have been missed because of lack of optical and X-ray instruments on board of *Fermi*, which are essential for revealing SNe associated with GRBs. This has motivated our search in the *Fermi* catalog for possible GRB-SN events.

Methods. The search for possible GRB-SN associations follows two requirements: (1) SNe should fall inside the *Fermi*/GBM error box of the considered long GRB, and (2) this GRB should occur within 20 days before the SN event.

Results. We have found five cases within $z < 0.2$ fulfilling the above reported requirements. One of them, GRB 130702A-SN 2013dx, was already known to have a GRB-SN association. We have analyzed the remaining four cases and we have concluded that three of them are, very likely, just random coincidences due to the *Fermi*/GBM large error box associated with each GRB detection. We found one GRB possibly associated with a SN 1998bw-like source, GRB 120121B/SN 2012ba.

Conclusions. The very low redshift of GRB 120121B/SN 2012ba ($z = 0.017$) implies a low isotropic energy of this burst ($E_{\text{iso}} = 1.39 \times 10^{48}$ erg). We then compute the rate of *Fermi* low-luminosity GRBs connected with SNe to be $\rho_{0,b} \leq 770 \text{ Gpc}^{-3} \text{ yr}^{-1}$. We estimate that *Fermi*/GBM could detect 1–4 GRBs-SNe within $z \leq 0.2$ in the next 4 years.

Key words. gamma-ray burst: general – supernovae: general

1. Introduction

Gamma-ray bursts (GRBs) are the most powerful stellar explosions in the universe (see Piran 2005; Gehrels & Mészáros 2012; Zhang 2014, for a review), with a total isotropic energy release of $E_{\text{iso}} = 10^{48-54}$ erg. Their origin is associated with the final collapse of very massive stars or with the merging of two compact objects. This first taxonomy was inferred from the existence of two observed classes for GRBs, based on their T_{90} duration (Klebesadel et al. 1982; Dezalay et al. 1992; Kouveliotou et al. 1993; Tavani 1998): GRBs with $T_{90} < 2$ s are named short GRBs; otherwise they are named long GRBs. All GRBs associated with supernovae (SNe) have been confirmed to be long bursts, although the opposite might not be true (Della Valle 2006; Fynbo et al. 2006; Gal-Yam et al. 2006). Observations carried out in the last decade suggest that long GRBs are associated with SNe Ib/c, which are believed to originate from the collapse of single very massive stars (Heger et al. 2003) or from moderate mass Wolf-Rayet stars in interacting binaries (Smartt 2009). To date, 35 GRB-SN associations have been confirmed on spectroscopic and/or photometric grounds (see Table 1). The

SN lightcurve peaks at 10–15 days after the GRB trigger (in the source rest-frame) powered by the radioactive decay of ^{56}Ni , and whose half-life time is about 6 days (Arnett 1996). Recently, it was proposed that GRB-SNe have the potential to be considered also as standardizable candles (Cano et al. 2014).

With the launch of satellites dedicated to GRBs studies, such as the *Swift* mission (Gehrels et al. 2009) and the *Fermi* spacecraft (Meegan et al. 2009), we have taken a step towards the understanding of GRB emission in the energy range between 0.3 keV and ~ 10 MeV. On the other hand, the Burst Alert Telescope (BAT, Barthelmy et al. 2005) on board *Swift*, is able to observe only a fraction of the sky that is 6.5 times smaller than that covered by the *Fermi* Gamma-ray Burst Monitor (GBM) detectors (Meegan et al. 2009). This implies that there could be long bursts, possibly connected with SNe, which have been detected by *Fermi*/GBM without soft X-rays and optical follow up, which are essential in order to reveal the presence of a SN in the GRB afterglow (Mangano et al. 2007). We can make a first order estimate of the expected number of *Fermi* long bursts connected with SNe as follows. If we restrict, for reasons of completeness, our analysis to GRB-SNe within $z \leq 0.2$, we have that *Swift*/BAT

Table 1. The sample of the 35 confirmed GRB-SN connections updated to 31 May 2014.

GRB	E_{iso} (erg)	Discovered by	z	SN identification	SN name	Refs.
970228	1.86×10^{52}	BATSE/SAX	0.695	bump		(Reichert 1997)
980326	5.60×10^{51}	BATSE/SAX	1(?)	bump		(Bloom et al. 1999)
980425	6.38×10^{47}	BATSE	0.0085	spec.	SN1998bw	(Galama et al. 1998)
990712	7.80×10^{51}	SAX	0.434	bump		(Frontera et al. 2009; Zeh et al. 2004)
991208	2.59×10^{53}	SAX	0.706	bump		(Frontera et al. 2009; Zeh et al. 2004)
000911	7.80×10^{53}	Konus-WIND	1.058	bump		(Lazzati et al. 2001; Hurley et al. 2000)
010921	1.10×10^{52}	HETE	0.45	bump		(Zeh et al. 2004)
011121	9.90×10^{52}	Ulysses	0.36	bump	SN 2001ke	(Bloom et al. 2002; Hurley et al. 2001; Greiner et al. 2003)
020305	$0.7\text{--}4.6 \times 10^{51}$	Ulysses	0.2\text{--}0.5	bump		(Gorosabel et al. 2005; Hurley et al. 2002b)
020405	1.28×10^{53}	Ulysses	0.695	bump		(Masetti et al. 2003; Hurley et al. 2002a)
020410	2.20×10^{52}	Konus-WIND	~ 0.5	bump		(Nicastrro et al. 2004; Levan et al. 2005)
021211	1.30×10^{52}	HETE	1.006	spec.	SN 2002lt	(Della Valle et al. 2003; Vreeswijk et al. 2003; Crew et al. 2002)
030329	1.70×10^{52}	Konus-WIND	0.168	spec.	SN 2003dh	(Golenetskii et al. 2003; Kawabata et al. 2003; Stanek et al. 2003)
030723	$<1.60 \times 10^{53}$	HETE	<1	bump		(Fynbo et al. 2003)
031203	9.99×10^{49}	INTEGRAL	0.105	spec.	SN 2003lw	(Soderberg et al. 2003; Tagliaferri et al. 2004)
040924	1.10×10^{52}	HETE	0.86	bump		(Fenimore et al. 2004; Soderberg et al. 2006c)
041006	3.50×10^{52}	HETE	0.716	bump		(Galassi et al. 2004; Bikmaev et al. 2004; Soderberg et al. 2006c)
050525A	3.39×10^{52}	Konus-WIND	0.606	spec.	SN 2005nc	(Della Valle et al. 2006)
060218	1.66×10^{49}	Swift	0.033	spec.	SN 2006aj	(Campana et al. 2006; Soderberg et al. 2006a)
060729	1.60×10^{52}	Swift	0.54	bump		(Cano et al. 2011; Parsons et al. 2006)
070419	7.90×10^{51}	Swift	0.97	bump		(Hill et al. 2007)
080319B	1.30×10^{54}	Swift	0.937	bump		(Perley et al. 2008; Kann et al. 2008; Cummings et al. 2008)
081007	2.50×10^{51}	Swift	0.5295	bump	SN2008hw	(Soderberg et al. 2008; Markwardt et al. 2008)
090618	2.90×10^{53}	Fermi/GBM	0.54	bump		(Izzo et al. 2012; Cano et al. 2011; McBreen 2009)
091127	1.60×10^{52}	Fermi/GBM	0.49	bump	SN 2009nz	(Cobb et al. 2010; Wilson-Hodge & Preece 2009)
100316D	9.81×10^{48}	Swift	0.059	spec.	SN 2010bh	(Bufano et al. 2012; Chornock et al. 2010; Sakamoto et al. 2010)
101219B	4.39×10^{51}	Fermi/GBM	0.55	spec.	SN 2010ma	(Sparre et al. 2011; van der Horst 2010)
111228A	7.52×10^{52}	Fermi/GBM	0.714	bump		(D'Avanzo et al. 2012; Briggs & Younes 2011)
120422A	1.28×10^{51}	Swift	0.283	spec.	SN 2012bz	(Melandri et al. 2012; Barthelmy et al. 2012)
120714B	4.51×10^{51}	Swift	0.3984	spec.	SN 2012eb	(Cummings et al. 2012; Klose et al. 2012)
120729A	2.30×10^{52}	Swift	0.80	bump		(Cano et al. 2014; Ukwatta et al. 2012)
130215A	3.10×10^{52}	Fermi/GBM	0.597	spec.	SN 2013ez	(de Ugarte Postigo et al. 2013; Younes & Bhat 2013)
130427A	9.57×10^{53}	Fermi/GBM	0.3399	spec.	SN 2013cq	(Melandri et al. 2014; Xu et al. 2013; von Kienlin 2013)
130702A	7.80×10^{50}	Fermi/GBM	0.145	spec.	SN 2013dx	(Cenko et al. 2013; Collazzi & Connaughton 2013; Singer et al. 2013)
130831A	4.56×10^{51}	Konus-WIND	0.4791	spec.	SN 2013fu	(Klose et al. 2013; Golenetskii et al. 2013)

has detected, to date, two such events, GRB 060218 (Campana et al. 2006) and GRB 100316D (Starling et al. 2011). Therefore, *Fermi*/GBM should have discovered $2_{-1.3}^{+2.6} \times \rho_{\text{GBM}}/\rho_{\text{BAT}} \times 0.6 = 2\text{--}11 \times 0.6 \sim 1\text{--}7$ GRB-SNe within $z \leq 0.2$. The ratio $\rho_{\text{GBM}}/\rho_{\text{BAT}}$ ($\rho_{\text{GBM}} = 238$ GRBs yr $^{-1}$, von Kienlin et al. 2014; $\rho_{\text{BAT}} = 95$ GRBs yr $^{-1}$, Sakamoto et al. 2011) takes into account the different sky coverage of both detectors and their different sensitivities (Band 2003), while the scale factor 0.6 accounts for the fact that *Fermi* has been monitoring the sky for 6 years, while *Swift* for 10 years. The attached 1σ Poissonian uncertainty at the rate of 2 GRB-SNe yr $^{-1}$, within $z \leq 0.2$, has been derived from Gehrels (1986).

We present in Sect. 2 the strategy that we have used to identify GRB-SN candidates. In Sect. 3 we discuss the 11 GRB-SN coincidences pinpointed by our code. In Sect. 4 we discuss our results and in Sect. 5 we present our conclusions.

2. Methodology and statistical analysis

Our code compares the positions of the Harvard catalog of SNe¹ and the Asiago SN catalog (Barbon et al. 2010) with the positions of 1147 long GRBs detected up to 31 May 2014, and reported in the *Fermi*/GBM catalog² with the attached error

¹ <http://www.cbat.eps.harvard.edu/lists/Supernovae.html>

² <http://heasarc.gsfc.nasa.gov/db-perl/W3Browse>

boxes. Subsequently, we considered only GRBs that were detected within Δt days before the occurrence of the SN. The exact value of Δt days was computed after taking into account several factors: the rise time of the SN (typically 10–15 days), the assumption that GRB and SN are simultaneous (Campana et al. 2006), and also the possibility that the SN was discovered after its maximum light. To discern physical GRB-SN associations by random spatial and temporal GRB-SN coincidences due to the large error box associated with GRB detections or uncertainties on the epoch of SN maximum, we also computed the statistical significance of GRB-SN associations for SN types for which we know a priori are not associated with GRBs, like SNe-Ia and Type II (see Valenti et al. 2005). In the first row of Table 2 we list the assumed Δt (in days) after the GRB trigger. In the following rows we list the cumulative number of possible associations, within Δt , for each type of SN, respectively, $N_{\text{Ib/c}}(\Delta t)$, $N_{\text{Ia}}(\Delta t)$, $N_{\text{IIp}}(\Delta t)$, and $N_{\text{IIc}}(\Delta t)$; and in the last row for all types, $N_{\text{tot}}(\Delta t)$. In the last column the percentage of the total number of each SN type over the total sample is also shown.

If we assume a random distribution of SNe in the sky, the spatial GRB-SN association follows the Poisson statistic, $e^{-\lambda} \lambda^n / n!$, where n is the number of observed associations and λ is the expected number of positive events in a chosen temporal window Δt . The expected number of positive events can be evaluated from $N_{\text{tot}}(\Delta t)$ (see last row in Table 2) times the percentage of each SN in the considered sample (see last column in Table 2). Therefore we have that $\lambda = N_{\text{tot}}(\Delta t) r_x$, where

Table 2. Cumulative number of each SN type associated within the error radius of *Fermi*-GRBs at different time intervals after the trigger time.

Δt (days)	10	20	30	40	50	60	70	80	90	100	110	120	150	200	300	400	500	r_x (%)
$N_{\text{Ib/c}}(\Delta t)$	8	9	9	13	13	15	17	18	18	20	21	26	30	42	68	81	96	12
$N_{\text{Ia}}(\Delta t)$	10	23	30	42	51	64	77	85	98	108	118	131	164	213	338	440	519	66
$N_{\text{IIp}}(\Delta t)$	2	4	8	14	16	19	19	21	22	26	27	30	39	54	82	103	124	16
$N_{\text{IIIn}}(\Delta t)$	1	2	4	6	8	9	9	9	10	11	11	11	14	21	30	38	51	6
$N_{\text{tot}}(\Delta t)$	31	67	98	136	166	209	240	260	288	314	338	378	471	627	893	1139	1399	100

Notes. In the first row the considered time intervals (in days) are listed. In the following rows the number of possible associations for each type of SN, respectively, Ib/c, Ia, IIp, and IIIn, and the total number of SNe, for each considered time interval, are listed. In the last column the percentage r_x of the total number of each SN type over the total sample is shown.

Fig. 1. Statistical significance of the GRB-SN occurrence as a function of the temporal window. This plot shows the significance of the deviation of SNe Ib/c in the time interval $(T_0, T_0 + 20 \text{ days})$ from the expected number of events assuming the relative proportion seen in the total SN sample.

$x = \{\text{Ib/c, Ia, IIp, IIIn}\}$. We then compared it with the observations $N_x(\Delta t)$, and evaluated the corresponding confidence levels. The results of the computation are shown in Fig. 1. A simple comparison of significance tracks reported in Fig. 1 between SNe Ib/c and other SN types shows that, as expected, only SNe Ib/c within $\sim 30\text{--}40$ days after the GRB triggers are suggestive of the existence of physical associations with GRBs. From a simple application of Poissonian statistics in a regime of small numbers (Gehrels 1986), we derive a threshold of $\geq 95\%$ confidence level, which corresponds to $\Delta t = 20$ days. In the following we will conservatively consider only associations between GRBs and SNe within 20 days of the GRB trigger.

3. The sample of GRBs-SNe Ib/c

The list of GRB-SN Ib/c associations that our code has pinpointed is shown in Table 3, together with observational properties of the bursts and possibly related SNe. We found five cases. One of them, GRB 130702A – SN 2013dx, is already known

(Singer et al. 2013)³. For all SNe the redshift is determined from spectral observations of the host galaxy.

The values of E_{iso} given in Table 4 are derived from the spectral analysis of *Fermi*/GBM data of GRBs, using a Band function (Band et al. 1993) as spectral model (see also Amati et al. 2008). We have considered time-tagged events (TTE) *Fermi*/GBM spectra which combine a high time resolution (up to $2 \mu\text{s}$) with a good resolution in the spectral range. We fitted these spectra with the RMfit package⁴. The value of E_{iso} in the last column of the table shows that all events are low-luminosity GRBs, unlike those events from so-called cosmological GRBs, characterized by $E_{\text{iso}} \sim 10^{51}\text{--}10^{54}$ erg.

³ If we relax the $z \leq 0.2$ constraint, our code detects three more well-known GRB-SN associations, specifically GRB 091127 – SN 2009nz (Troja et al. 2012), GRB 101219B – SN 2010ma (Sparre et al. 2011), and GRB 130427A – SN 2013cq (Xu et al. 2013; Melandri et al. 2014).

⁴ http://Fermi.gsfc.nasa.gov/ssc/data/analysis/rmfit/vc_rmfit_tutorial.pdf

Table 3. Main parameters of the *Fermi* GRB sample presented in this work and of the supernovae associated with these bursts.

GRB	RA GBM (deg)	Dec GBM (deg)	Error radius (deg)	T_{90} (s)	Fluence (0.01–1) MeV (erg cm ⁻²)	Peak flux (0.01–1) MeV (photon cm ⁻²)	SN	Date discovery	RA SN (deg)	Dec SN (deg)	z
090320B	183.4	49.8	9.5	29.2	1.67×10^{-6}	4.35 ± 0.25	2009di	2009 03 21	174.2411	45.0141	0.13
090426B	17.6	-19.2	18.1	16.1	6.77×10^{-7}	2.03 ± 0.18	2009em	2009 05 05	8.6855	-8.3993	0.006
110911A	258.58	-66.98	50.0*	8.96	5.94×10^{-7}	2.38 ± 0.41	2011gw	2011 09 15	112.0709	-62.3552	0.01
120121B	235.67	-39.34	7.9	18.4	1.95×10^{-6}	2.66 ± 0.21	2012ba	2012 01 21	230.6047	-38.2012	0.017
130702A	228.15	16.58	13.02	59	6.3×10^{-6}	7.03 ± 0.86	2013dx	2013 07 08	217.3116	15.7740	0.145

Notes. We also report the already known GRB-SN connection that we have found with our code in the last row of the table. (*) Nominal maximum value for the error radius of bursts detected by a single GBM detector.

Table 4. Results of the spectral fits of *Fermi*/GBM observations for the four GRBs with evidence of association with a SN Ic.

GRB	α	β	E_{peak} (keV)	E_{iso} (erg)
090320B	-0.65 ± 0.35	-2.42 ± 0.30	62.6 ± 12.0	9.13×10^{49}
090426B	-0.50 ± 3.12	-1.65 ± 0.15	39.9 ± 76.9	1.94×10^{47}
110911A	-0.47 ± 0.50	-1.36 ± 0.18	44.8 ± 20.1	6.22×10^{47}
120121B	-0.73 ± 0.21	-2.95 ± 0.89	92.2 ± 12.2	1.39×10^{48}

3.1. GRB 090320B – SN 2009di

GRB 090320B was detected by the *Fermi*/GBM detectors numbers 10 and 11 and also by Konus-WIND. The T_{90} duration reported by *Fermi* is 29.2 s, while unfortunately we do not have further information from Konus-WIND for this trigger. The possibly associated SN is SN 2009di, which was discovered on 21 March 2009, just one day after the detection by *Fermi*, by the CRTS (Drake et al. 2009). At the moment of the discovery, the unfiltered magnitude of the SN was 18.6. Spectroscopy made with the 5.1 m Palomar *Hale* telescope identified SN 2009di as a Type Ic SN. The redshift of the SN was reported to be $z = 0.13$. The distance between the SN and *Fermi* positions one is 7.8 degrees, while the *Fermi* error radius is about 9.5 degrees.

3.2. GRB 090426B – SN 2009em

GRB 090426B was observed by detectors 3 and 5 of *Fermi*/GBM, with a T_{90} duration of 16.1 s. SN 2009em, associated with this GRB, was discovered by Monard (2009) on 5 May 2009. Follow-up observations made 6 days later confirmed the presence of an unfiltered magnitude 16.6 supernova. Further spectroscopic observations (Navasardyan & Benetti 2009; Folatelli & Morrell 2009) made around May 19 confirmed the Ic nature of this SN, which corresponds to several known SNe Ic observed about one month from the maximum light, which plays against an association with GRB 090426B. The distance from the *Fermi* position is 13.8 degrees, to be compared with an error radius of 18 degrees. The redshift of this source was measured to be $z = 0.006$, which corresponds to a comoving distance of 25.31 Mpc.

3.3. GRB 110911A – SN 2011gw

This GRB triggered the *Fermi* detectors numbers 2 and 10. However, the signal from detector number 2 was dominated by noise, so we have considered only the flux detected by number 10. This GRB was characterized by $T_{90} = 8.96$ s. SN 2011gw

was discovered on 15 September by different observers as an object of magnitude approximately 17.4 (Pignata et al. 2011). A spectrum obtained one month later, on 20 October, at the NTT telescope revealed the Ib/c nature of this supernova, and a cross-check with the GELATO library found a match with other SNe at about two months post maximum. The redshift of this SN was reported to be 0.01 while the distance between the center of *Fermi*/GBM detectors and the SN was 48 degrees, with an error radius of 50 degrees. This large error box is due to the combination of two detectors that are located on the opposite sides of the *Fermi* spacecraft and that increase the probability of a casual association for this GRB-SN event.

3.4. GRB 120121B – SN 2012ba

GRB 120121B was detected by the *Fermi* detectors numbers 3 and 5. The T_{90} duration was of 18.4 s. The best fit of the integrated spectrum of the GRB is a Band function with an intrinsic peak energy of $E_{\text{peak},i} = (92.2 \pm 12.2)$ keV. The SN associated with this GRB may be SN 2012ba. It was discovered on 21 January, the same day of the GRB trigger, as an object of unfiltered magnitude 16.6 (Pignata et al. 2012), still in rising phase. A spectrum obtained on 2 March (40 days after the discovery) with the 6.5 m *Magellan II Clay* telescope and then cross-correlated with the SNID libraries of SN spectra, showed a match with a Type Ic SN more than 15 days after maximum. The redshift of the SN, $z = 0.017$ associated with the observed peak magnitude of 15.9, eleven days after the SN discovery (Pignata et al. 2012), implied an absolute magnitude at maximum of -18.5 , which is an upper limit to the intrinsic luminosity, considering the correction for dust extinction. This result suggests that SN 2012ba is a very luminous SN Ic, with an absolute magnitude similar to that of SN 2010bh, $R_{\text{abs}} \approx -18.5$ (Bufano et al. 2012), or even brighter, similarly to SN 1998bw $R_{\text{abs}} \approx -19$ (Patat et al. 2001). The distance between the SN position and the *Fermi* center was of 4.1 degrees, inside the *Fermi* error radius of 7.9 degrees.

4. Discussions

Our analysis discovered five GRB-SN coincidences within $z \leq 0.2$, and one of them was already known to be a physical association between GRB and SN (GRB 130702A-SN 2013dx; Singer et al. 2013). We note that the afterglow of GRB 130702A has been found by the authors of the above cited work upon searching 71 deg² surrounding the *Fermi*/GBM localization. This result further strengthens the reliability of the adopted methodology.

After discussion of the data, we found that SN 2012ba is the only bona fide candidate for being physical associated with a GRB (120121B). SN 2012ba was of Type Ic and quickly

reached a very bright maximum magnitude $R_{\text{abs}} \simeq -19$ about 11 days after the GRB trigger (Kryachko et al. 2012), which is very similar to the typical rising time of SNe associated with GRBs (Bufano et al. 2012). To date there are only two other SNe associated with GRBs and classified as Ic (rather than broad lines Ic or Hypernovae): SN 2002lt, associated with GRB 021211 (Della Valle et al. 2003), and SN 2013ez, associated with GRB 130215A (Cano et al. 2014). However, these observations do not imply that GRBs may be associated with standard Type Ic SNe. We note that in all three cases, 2012ba, 2002lt, and 2013ez, SN spectra were secured 20–40 days past maximum; therefore, even if the pre-maximum spectra showed significantly broader lines than observed in the post-maximum spectra, this difference shortly vanished after maximum (if the SN ejecta carry little mass) such that it is not easy to distinguish between the two types of SNe. The isotropic energy of this *Fermi* GRB-SN candidate is $E_{\text{iso}} = 1.39 \times 10^{48}$ erg, which implies that this burst belongs to the low-luminosity subclass of GRBs (Guetta & Della Valle 2007; Piran et al. 2013; Tsutsui & Shigeyama 2014). Now, we are in the position to independently estimate, admittedly on the very scanty statistic of one single object, the rate ρ_0 of local low-energetic long GRBs–Type Ic SNe. Following Soderberg et al. (2006b) and Guetta & Della Valle (2007), we have computed the photon peak flux f_p in the energy band 1–1000 keV and the corresponding threshold peak flux, following the analysis of Band (2003) for GRB 120121B. In this way we have evaluated the maximum redshift z_{max} at which this burst would have detected, $z = 0.0206$, and then the corresponding maximum comoving volume V_{max} .

The empirical rate can then be written as

$$\rho_0 = \frac{N_{\text{LE}}}{V_{\text{max}} f_p T}, \quad (1)$$

where $N_{\text{LE}} = 1$ is the number of found physical connections, $f_p \approx 0.76$ the average ratio of *Fermi* solid angle over the total, and $T = 6$ years the *Fermi* observational period. We infer a local rate for this GRB–SN Ic events of $\rho_0 = 77^{+289}_{-73} \text{ Gpc}^{-3} \text{ yr}^{-1}$, where the errors are determined from the 95% confidence level of the Poisson statistic (Gehrels 1986). There is growing body of evidence that low-luminosity GRBs are less beamed than high luminosity GRBs, indeed f_b^{-1} is on the order of 10, or less (see, e.g., Guetta & Della Valle 2007). After taking into account this correction we derive $\rho_{0,b} \leq 770 \text{ Gpc}^{-3} \text{ yr}^{-1}$, which is consistent with $\rho_0 = 380^{+620}_{-225} \text{ Gpc}^{-3} \text{ yr}^{-1}$ in Guetta & Della Valle (2007), $325^{+352}_{-177} \text{ Gpc}^{-3} \text{ yr}^{-1}$ in Liang et al. (2007), and $230^{+490}_{-190} \text{ Gpc}^{-3} \text{ yr}^{-1}$ in Soderberg et al. (2006b).

This analysis confirms the existence of a class of more frequent low-energetic GRBs–SNe Ic, whose rate is larger than the one obtained extrapolating at low redshifts the rate for high-energetic bursts, i.e., $\rho = 1.3^{+0.7}_{-0.6} \text{ Gpc}^{-3} \text{ yr}^{-1}$ (Wanderman & Piran 2010).

5. Conclusions

This paper presents the results of an analysis dedicated to finding possible connections between long GRBs listed in the *Fermi*/GBM catalog and SNe. Our analysis was motivated by the fact that we expected, on a statistical basis, to find in the *Fermi* catalog between one and seven GRB-SN connections within $z < 0.2$. From our analysis the following results emerge:

- we have found a total number of five possible connections at $z \leq 0.2$. One of them was already known as having physical GRB-SN associations. After discussing the remaining

four cases, we found that only GRB 120121B is very likely physically connected with SN 2012ba. This result of two observed GRBs–SNe is fully consistent with our initial estimate of 1–7 low- z events being found in the *Fermi* catalog;

- the very low redshift at which GRB 120121B/SN 2012b is observed implies a small isotropic energy emitted during the GRB, $E_{\text{iso}} = 1.39 \times 10^{48}$ erg. From this single connection, we compute the rate of *Fermi* low-luminosity GRBs connected with SNe to be $\rho_0 = 77^{+289}_{-73} \text{ Gpc}^{-3} \text{ yr}^{-1}$. If we consider an additional correction, due to a beaming in the low-luminosity GRB emission, f_b^{-1} on the order of 10 (Guetta & Della Valle 2007), we obtain for the *Fermi* rate $\rho_{0,b} \leq 770 \text{ Gpc}^{-3} \text{ yr}^{-1}$, which is consistent with $\rho_0 = 380^{+620}_{-225} \text{ Gpc}^{-3} \text{ yr}^{-1}$ in Guetta & Della Valle (2007), $325^{+352}_{-177} \text{ Gpc}^{-3} \text{ yr}^{-1}$ in Liang et al. (2007), and $230^{+490}_{-190} \text{ Gpc}^{-3} \text{ yr}^{-1}$ in Soderberg et al. (2006b);
- if we consider a continuous time coverage, including previous analysis from *Beppo*/SAX (7 years, 1 connection – GRB 980425, Galama et al. 1998) and *Swift* (9 years, 2 connections – GRB 060218, Campana et al. 2006; and GRB 100316D, Bufano et al. 2012), we obtain a comprehensive rate of $\rho_0^{\text{tot}} = 31^{+40}_{-20} \text{ Gpc}^{-3} \text{ yr}^{-1}$, which becomes $\rho_{0,b}^{\text{tot}} = 310^{+400}_{-200} \text{ Gpc}^{-3} \text{ yr}^{-1}$, assuming f_b^{-1} on the order of 10;
- on the basis of the annual rate of *Fermi* GRBs (238 GRBs/year), and of the expected number of *Fermi*/GBM bursts associated with low- z SNe (1–7 GRBs) in 6 years of observations, we estimate that in the next 4 years *Fermi*/GBM could detect ~ 1 –4 GRBs–SNe within $z \leq 0.2$.

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