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

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ABSTRACT

Context. Observations suggest that the major fraction of long duration gamma-ray bursts (GRBs) are connected with broad-linewidth supernovae Ib/c (SNe-Ib/c). The presence of GRB-SN 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) which is about 6.5 times larger than the FoV of Swift, therefore we expect that a number of GRB-SN connections have been missed due to lack of optical and X-ray instruments on board of Fermi, which are essential to reveal SNe associated with GRBs. This fact has motivated our search in the Fermi catalogue for possible GRB-SN events.

Methods. The search for possible GRB-SN associations follows two requirements: (1) SN 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 5 cases, within \( z < 0.2 \) fulfilling the above reported requirements. One of them, GRB 130702A-SN 2013dx, was already known as GRB-SN association. We have analyzed the remaining 4 cases and we 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, 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 \( E_{\text{iso}} = 1.39 \times 10^{54} \) erg. We then compute the rate of Fermi low-luminosity GRBs connected with SNe to be \( \rho_{\text{GRB}} \leq 770 \) Gpc\(^{-3}\) yr\(^{-1}\). We estimate that Fermi-GBM could detect 1–4 GRB-SNs within \( z \leq 0.2 \) in the next 4 years.

Key words. Gamma-ray burst: general — Stars : supernovae : general — Cosmology : observations

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 \( E_{\text{iso}} = 10^{54} – 10^{55} \) erg. Their origin is associated to the final collapse of a very massive star or to 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).

With the launch of satellites dedicated to GRBs studies, as the Swift mission (Gehrels et al. 2009), and the Fermi spacecraft (Meegan et al. 2009), we made a step forward towards the understanding of GRB emission in the energy range between 0.3 keV up to ~ 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 which is 6.5 times smaller than the one covered by the Fermi-Gamma Ray Burst Monitors (GBM) detectors (Meegan et al. 2009). This fact implies that there could exist long bursts, possibly connected with SNe, which have been detected by Fermi-GBM without soft X-rays and optical follow up, which are essential to reveal the presence of a SN in the GRB afterglow (e.g. Mangano et al. 2007). We can make a first order estimate of the expected number of Fermi long bursts connected with SNe as it follows. If we restrict, for reason of completeness, our analysis to GRB-SNe within \( z \leq 0.2 \), we have that Swift-BAT has detected, to date, two such events (GRB 060218, Campana et al. 2006) and (GRB 100316D, Star...
Our code compares the positions of the Harvard catalog of SNe and the Asiago SN catalog, with the positions of 1147 long GRBs detected up to May 31th, 2014, and reported in the Fermi-GBM catalog with the attached error boxes. Subsequently, we consider only GRBs which 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 have computed the statistical significance of GRB-SN associations also for SN types for which we know “a priori” that they are not associated with GRBs, like SNe-Ia and type II (see Valenti et al. 2005). In Table 3, we list in the first row 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 \(N_{\text{tot}}(\Delta t)\), \(N_{\text{tot}}(\Delta t)\), and in the last one for all types, \(N_{\text{tot}}(\Delta t)\). In the last column is also shown the percentage of the total number of each SN type over the total sample.

We present in Section 2 the adopted strategy that we have used to identify GRB-SN candidates. In Section 3 we discuss our results and in Section 5 we present our conclusions.

### 2. Methodology and statistical analysis

Our code compares the positions of the Harvard catalog of SNe and the Asiago SN catalog, with the positions of 1147 long GRBs detected up to May 31th, 2014, and reported in the Fermi-GBM catalog with the attached error boxes. Subsequently, we consider only GRBs which 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 have computed the statistical significance of GRB-SN associations also for SN types for which we know “a priori” that they are not associated with GRBs, like SNe-Ia and type II (see Valenti et al. 2005). In Table 3, we list in the first row 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 \(N_{\text{tot}}(\Delta t)\), \(N_{\text{tot}}(\Delta t)\), and in the last one for all types, \(N_{\text{tot}}(\Delta t)\). In the last column is also shown the percentage of the total number of each SN type over the total sample.

If we assume a random distribution of SNe in the sky, the spatial GRB-SN association follows the Poisson statistic, \(e^{-\lambda}\frac{\lambda^n}{n!}\), where \(n\) is the number of observed associations and \(\lambda\) 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 \(\lambda = N_{\text{tot}}(\Delta t)\), where \(x = (1/c, 1/L, 1/P, 1/N)\). We have then compared it with the observations \(N(x, \Delta t)\), and evaluated the corresponding confidence lev-
Table 2. The cumulative number of each SN type associated within the error radius of Fermi-GRBs at different time intervals after the trigger time. 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 IIn, and the total number of SNe, for each considered time interval, are listed. In the last column the percentage $r_c$ of the total number of each SN type over the total sample is shown.

| $\Delta t$ (days) | 10  |
|------------------|-----|
| $N_{Ib/c}(\Delta t)$ | 8   |
| $N_{Ia}(\Delta t)$ | 23  |
| $N_{IIp}(\Delta t)$ | 1   |
| $N_{IIn}(\Delta t)$ | 31  |
| $N_{tot}(\Delta t)$ | 100 |

Fig. 1. The 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 $(T_0 - 20$ days) from the expected number of events assuming the relative proportion seen in the total SN sample.

![Graph showing the statistical significance of GRB-SN occurrence](image)

The results of the computation are shown in Fig. 1. A simple comparison of significance tracks reported in Fig. 1 between SNe-Ibc and other SN types shows that, as expected, only SNe Ib/c within ~ 30 – 40 days after the GRB triggers are suggestive of the existence of physical associations with GRBs. From a simple application of Poissonian statistic in regime of small numbers (Gehrels 1986), we derive a threshold of ≥ 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 from 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 reported in Table 3 together with observational properties of the bursts and possibly related SNe. We found 5 cases. One of them, GRB 130702A - SN 2013dx is already known (Singer et al. 2013). For all SNe the redshift is determined from spectral observations of the host galaxy.

3.1. GRB 090320B - SN 2009di

GRB 090320B was detected by the 10 and 11 Fermi GBM detectors and also by Konus-WIND. The $T_0$ 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, by Troja et al. (2012), GRB 101219B - SN 2010ma (Sparre et al. 2011), GRB 130427A - SN 2013cq (Xu et al. 2013). Melandri et al. (2014). The values of $E_{iso}$ reported 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 $\mu$s) with a good resolution in the spectral range. We fitted these spectra with the RMIT package. The value of $E_{iso}$ in the last column of the table shows that all events are low luminosity GRBs, unlike from so called “cosmological” GRBs, characterized by $E_{iso} \sim 10^{51} – 10^{54}$ erg.

4 http://Fermi.gsfc.nasa.gov/ssc/data/analysis/rmfit/vc_rmfit_tutorial.pdf
The redshift of the SN was reported to be \( \leq 0.21 -2.95 \) (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, similar to SN 1998bw \( R_{\text{abs}} \approx -19 \) (Patat et al. [2001]). The distance between the SN position and the \( \text{Fermi} \) center was of 4.1 degree, inside the \( \text{Fermi} \) error radius of 7.9 degree.

### 4. Discussions

Our analysis discovered 5 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\,s. 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 $\rho_0$ 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 $z_{\text{max}}$, at which this burst would have detected, $z = 0.0206$, and then the corresponding maximum comoving volume $V_{\text{max}}$.

The empirical rate can then be written as

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

where $N_{\text{LE}}$ is the number of found physical connections, $f_p \approx 0.76$ the average ratio of Fermi solid angle over the total one, and $T = 6$ years is the Fermi observational period. We infer a local rate for this GRB–SN Ic events of $\rho_0 = 7.7^{+290}_{-73}$ Gpc$^{-3}$ 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 $f_p^{-1}$ is of the order of 10, or less (see e.g. Guetta & Della Valle 2007). After taking into account this correction we derive $\rho_{0,b} \leq 770$ Gpc$^{-3}$ yr$^{-1}$, which is consistent with $\rho_0 = 380^{+6200}_{-132}$ Gpc$^{-3}$ yr$^{-1}$ in Guetta & Della Valle (2007), $325^{+332}_{-140}$ Gpc$^{-3}$ yr$^{-1}$ in Liang et al. (2007), and $230^{+2990}_{-140}$ Gpc$^{-3}$ 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., $\rho = 1.3^{+1.0}_{-0.6}$ Gpc$^{-3}$ yr$^{-1}$ (Wanderman & Piran 2010).

5. Conclusions

This paper presents the results of an analysis dedicated to find possible connections between long GRBs listed in the Fermi–GBM catalog and SNe. Our analysis was motivated by the fact that we expected, on statistical basis, to find in the Fermi catalog a minimum of 1 up to 7 one GRB-SN connections within $z < 0.2$. From our analysis the following results emerge:

- we have found a total number of 5 possible connections at $z \lesssim 0.2$. One of them was already known as physical GRB-SN associations. After discussing the remaining 4 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 to be found in the Fermi catalogue;

- 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 $\rho_0 = 77^{+290}_{-73}$ Gpc$^{-3}$ yr$^{-1}$. If we consider an additional correction, due to a beaming in the low luminosity GRB emission, $f_p^{-1}$ of the order of 10 (Guetta & Della Valle 2007), we obtain for the Fermi rate $\rho_{0,b} \leq 770$ Gpc$^{-3}$ yr$^{-1}$, which is consistent with $\rho_0 = 380^{+6200}_{-132}$ Gpc$^{-3}$ yr$^{-1}$ in Guetta & Della Valle (2007), $325^{+332}_{-140}$ Gpc$^{-3}$ yr$^{-1}$ in Liang et al. (2007), and $230^{+2990}_{-140}$ Gpc$^{-3}$ 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. 1999) 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 $\rho_{0,b} = 31^{+460}_{-31}$ Gpc$^{-3}$ yr$^{-1}$, which becomes $\rho_{0,b} = 310^{+4600}_{-31}$ Gpc$^{-3}$ yr$^{-1}$, assuming $f_p^{-1}$ of 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 $z \lesssim 0.2$.

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