Properties of Low Luminosity Afterglow Gamma-ray Bursts

H. Dereli1⋆, M. Boër1⋆⋆, B. Gendre1,2,3, L. Amati4, and S. Dichiara5

1 ARTEMIS (CNRS UMR 7250, OCA, UNS); Boulevard de l’Observatoire, CS 34229, 06304 Nice Cedex 4, France
2 Eramus Mundus Joint Doctorate IRAP PhD student
3 University of the Virgin Islands, 2 John Brewer’s Bay road, 00802 St Thomas, V.I., USA
4 IASF-Bologna/INAF; Area della Ricerca di Bologna, Via Gobetti 101, 40129 - Bologna, Italy
5 University of Ferrara; Via Savonarola 9, 44121 Ferrara, Italy

Received —; Accepted —

ABSTRACT

Aims. We characterize a sample of Gamma-Ray Bursts with low luminosity X-ray afterglows (LLA GRBs), and study their properties.

Methods. We select a sample consisting of the 12% faintest X-ray afterglows from the total population of long GRBs (lGRBs) with known redshift. We study their intrinsic properties (spectral index, decay index, distance, luminosity, isotropic radiated energy and peak energy) to assess whether they belong to the same population than the brighter afterglow events.

Results. We present strong evidences that these events belong to a population of nearby events, different from that of the general population of lGRBs. These events are faint during their prompt phase, and include the few possible outliers of the Amati relation. Out of 14 GRB-SN associations, 9 are in LLA GRB sample, prompting for caution when using SN templates in observational and theoretical models for the general lGRBs population.

Key words. Gamma-ray: bursts – supernovae: type Ibc – Gamma-ray bursts: afterglow

1. Introduction

Gamma-ray bursts (GRBs) are the most luminous events in the Universe, with isotropic luminosity between $10^{54} \ldots 10^{55}$ erg s$^{-1}$ (Mészáros 2006). GRBs display two components: the prompt emission, followed by an afterglow (Rees & Mészáros 1992; Mészáros & Rees 1997; Panaitescu et al. 1998), both observed at all wavelengths (Costa et al. 1997; Van Paradijs et al. 1997; Frail et al. 1997). In X-rays, the afterglow light curve can be described as a steep-flat-steep broken power law (Nousek et al. 2006). The first part (steep decay) has been associated with the prompt phase (Willingale et al. 2007; Zhang et al. 2006) while the central engine is still active; the rest of the afterglow is due to the dynamics of the interaction of the jet with the surrounding medium.

Several studies have been made on GRB samples (e.g. Melandri et al. 2014), but in general they do not address specific properties. Usually the authors focus on complete samples in order to derive broad properties. These properties are then used to define the unknown physical properties of an archetypal GRB. In this work, we consider that the population of long GRBs (hereafter IGRBs) may hide various sub-types of GRBs; thus it is important to check for the existence of different populations in the sample, and, should this happen, how the previous conclusions apply to the whole populations. This has already been shown with the class of ultra-long GRBs (Gendre et al. 2013; Zhang et al. 2014; Boër, Gendre & Stratta 2014).

In the past, several GRBs featuring faint prompt emission have been observed: GRB 980425 (Galama et al. 1998; Kulkarni et al. 1998; Pian et al. 2006, e.g.), GRB 031203 (e.g. Malesani et al. 2004; Soderberg et al. 2004; Watson et al. 2004), GRB 060218 (Campana et al. 2006; Mazzali et al. 2006; Soderberg et al. 2006; Virgili et al. 2009, e.g.) and GRB 100316D (Fan et al. 2011; Starling et al. 2011, e.g.). Theoretical work has been done on the standard model in order to explain these events (Daigne & Mochkovitch 2007; Barniol-Duran et al. 2015, e.g.), and from their obvious properties (a low luminosity) several authors have pointed out that only very few faint events are detected (e.g. Imperio et al. 2005). All these studies are based on the properties of single events (despite the fact that GRB 060218 and GRB 980425 have very different properties, for instance), and so far the global sample of Swift prompt faint events has not been studied. Moreover, to our knowledge, despite a different approach and properties, no systematic study (and actually no individual) has been made by selecting a sample on the basis of the faintness of the afterglow.

This is the purpose of this work, and in the following we call GRB displaying dim afterglow (according to our criteria, Low Luminosity Afterglow GRBs (LLA GRBs). We explicit the criteria to build a consistent sample of LLA GRBs and we derive its properties. Then, we use a control sample based on different bursts to check whether they form a class different from that of normal IGRBs.

This paper is organized as follows: In section 2 we present the LLA GRB sample and we describe how we selected it. In section 3 we discuss the possible biases and basic properties of our sample. In section 4 we discuss our results, before concluding in section 5. In the following, all errors are quoted at the 90% confidence level, and we used a standard flat $\Lambda$CDM model with $\Omega_m=0.3$ and $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$. We also used the standard notation $F \propto t^{-\alpha} \nu^{-\beta}$. 
2. Definition of the sample

We took into account all bursts with a measured redshift observed before 2013, February the 15th, without consideration of the detector triggered by the event and/or observing it. We have used the list compiled by Greiner. This leads to a first sample of 283 sources which have been observed at X-ray wavelengths, including short and long GRBs. As we are interested only in the later, we have to exclude sGRBs; to that purpose we used the method described in Sniezalez et al. (2013); this method classifies short GRBs all burst with a duration less than 2 seconds in the rest frame, with additional criteria on the afterglow) to reject them, leaving 254 long bursts in the global sample.

As the analysis of the bursts that happened prior to 2006 was already performed by Gendre et al. (2008), we describe here the method followed for the Swift bursts only. We retrieved the XRT light curve from the online Swift repository (Evans et al. 2009).

Comparing flux light curves is a complex task, and need a careful estimation of the spectral index and the count-to-flux conversion factor. The estimation of these two parameters are done automatically for the online repository light curve, using standard models that may fail for various reasons, or not correspond to our needs (for instance, a spectral index estimated with some data taken before the end of the plateau phase, see below). We thus cannot use directly the data downloaded from the online repository, and needed to estimate independently the spectral index and the count-to-flux conversion factor.

For this purpose, we also downloaded the raw data from the archives, and applied to them the calibration released in May 2013 (using the Swift software, distributed as part of the HEASOFT package, version 6.12). We then extracted a spectrum using the task xselect, also part of the HEASOFT package, and fit it with a power law model absorbed twice, in the host galaxy and in the Milky-Way. The N_H value of the Galaxy was set to the value given by the Leiden/Argentina/Bonn (LAB) Survey of Galactic HI (Kalberla et al. 2005), while the one for the host was left free to vary at the host redshift. Finally we compared this best fit model with the one from the automated analysis pipeline: in case of inconsistency we recomputed the flux light curve using the conversion found from our best fit model.

Once the flux calibration has been checked and eventually corrected, we selected the afterglow part of the light-curve. We followed the method of Gendre et al. (2008), removing from the light curves all emission present before the end of the plateau phase and all flaring emissions. This net light curve was then corrected taking into account the cosmological effects including the K-correction.

We worked on a "flux" light curve, rescaling all light curves to a common distance of $z = 1$. As stated in Gendre & Boër (2005), this allows a smaller uncertainty on the final light curves. One may wonder, now with the precise cosmology parameters measured by Planck (Hinshaw et al. 2013; Ade et al. 2013) whether this is really needed; the reason is that the uncertainty is introduced by the K-correction (and not by the distance correction), which is very sensitive to the spectral index:

$$K \propto (1 + z)^n$$  \hspace{1cm} (1)

As an example, with a redshift of 4 and a precision of 1.0±0.3 for $\beta$, the uncertainty on K is 5±3, i.e. 60%. Rescaling to $z = 1$ leads to 2.5±0.7, i.e. an uncertainty of 28%: this method reduces the scattering induced by the uncertainties on the measurements, allowing for a more precise selection of the sample.

Being interested on LL A events, we defined two template afterglows with a decay index of 1.2 and 1.4 respectively (corresponding to the typical values expected with $p \sim 2.3$ where $p$ is the power law index of the accelerated electrons in the cases of wind and interstellar media); we set a $priori$ the limit at $F = 1 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ one day after the burst.

There are two reasons for this choice: first, we are interested in the low luminosity part, and thus we chose a flux significantly lower than the mean observed flux for the afterglows present in Fig. 1. As the analysis of the bursts that happened prior to 2006 was already performed by Gendre et al. (2008), there are bursts with a low luminosity that seems to not follow the properties of the other groups. These events represent about 10% of the total burst population, which turns to a limiting flux of about $10^{-13}$ erg cm$^{-2}$ s$^{-1}$ one day after the burst. Additionally, the flux cutoff $10^{-13}$ erg cm$^{-2}$ s$^{-1}$ at 1 day corresponds roughly to the lowest afterglow luminosity at one day of the unbiased sample of D’Avanzo et al. (2012a) (there in as seen from Figure 2).

All bursts with an afterglow light curve entirely below these two templates were part of LLA GRBs sample; the others are used as a control sample. The result of the selection is displayed in Fig. 1.

The final sample includes 31 events that are listed in Table 1 representing about 12% of all IGRBs considered here. Table 1 displays the GRB name, redshift, galactic and host N_H, galactic and host A_V, the afterglow temporal and spectral indexes, the isotropic and peak energies, and the T_90 duration (the time during which 90% of the energy of the prompt is emitted). For those afterglows displaying a break after the plateau phase (GRB 060614 and GRB 120729A), the decay index is indicated pre-break.

### 3. Statistical Properties

#### 3.1. The redshift distribution

The redshift distributions of the LLA GRB sample is shown in Fig. 2 together with the distribution of all IGRBs.

A simple examination of Fig. 2 shows that LLA GRBs are closer than normal IGRBs whose distribution peaks on average at $z = 2.2$ (e.g. Jakobsson et al. 2006; Coward et al. 2013). Table 2 displays the main parameters of the two distributions.

Table 2. Statistical parameters of the cumulative redshift distributions.

| Parameter | LLA GRBs | All IGRBs |
|-----------|----------|-----------|
| mean      | 0.55     | 2.20      |
| median    | 0.53     | 1.98      |
| standard deviation | 0.38     | 1.19      |

We check now whether the difference between the two redshift distribution is intrinsic or due to a selection bias.

Faint events are more difficult to detect than brighter ones. Furthermore, the measure of the redshift implies that the optical afterglow is bright enough for spectroscopic observations to be performed. As a matter of consequence, LLA GRBs are plagued by a detection bias that prevent them to be detected at large distance. From their flux, we estimate that the faintest of the LLA GRBs present in our sample can be detected up to a distance...
distance of $z = 1$. Because regular IGRBs can be detected up to $z \approx 8.2$ (Tanvir et al. 2009), we also consider that the sample of IGRBs is complete for $z < 1$, thus removing the detection bias. We have recomputed the cumulative redshift distributions for this sub-sample (see Fig. 3). The difference is still large, and from a Kolmogorov-Smirnov test the probability that the two distributions are drawn from the same population is $9.4 \times 10^{-4}$. We thus conclude that the LLA GRB population is different from the "classical" IGRBs one.

3.2. Absorption and Extinction

For consistency, we first checked that our distribution for the Milky Way values of $A_{V,Gal}$ and $N_{H,Gal}$ (i.e. the optical extinction and X-ray absorption parameters) is consistent with the whole sample of normal long GRBs. While the X-ray absorption has little effect on our sample since we use the flux in the 2.0-10.0 keV band, where absorption can be neglected (Morrison et al. 1983), it is well known that the optical extinction can bias a distribution (for instance the well known problem of dark bursts, e.g. Jakobsson et al. 2004).

The optical extinction was calculated using the NASA/IPAC extragalactic database\(^4\) for the Landolt V band measured by Schlegel et al. (1998) for all bursts but GRB 060904B and GRB 061110A. These two bursts are seen in projection on the galactic disk where the measures of Schlegel et al. (1998) are highly variable with the position. For these two events, we rely on the most accurate measurements of Schady et al. (2012) and Zafar et al. (2011) respectively. The results are reported in Fig. 2. One can note that the $A_V$ values obtained for LLA GRBs statistically are not very larger compare to the one for normal IGRBs ($A_V < 2$ for 87% of normal IGRBs, Covino et al. 2013). In the following, we consider that the gas and dust in the Galaxy have not introduced a bias in LLA GRB sample.

The intrinsic hydrogen column density $N_H$ can be linked to the host properties (Reichart & Price 2002), thus we also investigated on this. The intrinsic host absorptions for the LLA GRBs are mostly compatible with little or no intrinsic absorption. We see that for the sources with a non zero $N_{H,X}$ (Fig. 5), the absorption of the host galaxy is on average a factor 10 larger than in the Milky Way, as already noted by Starling et al. (2013). At low redshift this effect was attributed to the gas in the host galaxy.

3.3. Decay and spectral index

The distributions of the temporal decays and spectral index for the LLA GRB sample are displayed in Fig. 6. We used a reference sample of bursts listed in Gendre et al. (2008) and not members of the LLA GRB subclass. Note that the decay index of GRB 060607A reported in this last article is incorrect and is not considered in the comparison. The two samples are very similar, as indicated by a K-S test ($p = 0.80$ and $p = 0.08$ for the decay and the spectral indices respectively). We thus conclude that the two samples have similar spectral and temporal properties. This can also be seen when considering the closure relations (Meszaros et al. 1998; Sari et al. 1998, 1999a; Chevalier & Li 2000; Zhang & Meszaros 2008) to investigate the burst geometry, the fireball microphysics, its cooling state and the surrounding medium (presented in Fig. 7). These are very similar to the ones obtain from BeppoSAX, XMM-Newton or Chandra (De Pasquale et al. 2006; Gendre et al. 2006) for long bursts. We note however two peculiar events:

1. GRB 120729A: The pre-jet break closure relations are rejected for this event. We can thus identify the break presents at $t_b = 8.1$ ks in the light curve as the jet break, obtaining the positions of the specific frequencies and the value of $p$ ($\nu_m < \nu_{XRT} < \nu_c$, $p = 2.8 \pm 0.2$). The pre-jet break decay properties are in agreement with this (green point in Fig. 7).

2. GRB 060614: This event would be compatible with another jet effect, with $p = 2.25 \pm 0.05$. However, the errors bars are large enough to accommodate some non jetted closure relations. We thus cannot conclude firmly on the jet hypothesis for this source based on the closure relations alone.

\(^4\) http://ned.ipac.caltech.edu/forms/calculator.html.
We also investigated the prompt properties of the LLA GRBs. For this purpose, as the BAT bandwidth is narrow, we used whenever possible the data from *Fermi* GBM. For events seen by Konus-Wind or BeppoSAX, we used previously published results. About half of the events have a firm measurement of the prompt parameters, the other half presenting upper and lower limits. We corrected for the cosmological redshift the values of $E_p$, obtaining the intrinsic $E_{p,i}$ values. These values cluster broadly within the 40–200 keV range.

We note however that there is a lack of bright events also in the prompt phase. Taking into account the median redshift of LLA GRBs, the $E_{p,i}$ values, the intrinsic scatter of the Amati relation, and the properties of the BAT instrument, one should expect to detect bursts up to $E_{p,i} = 3 \times 10^{53}$ ergs, at least one order of magnitude larger than the brightest measurements listed in Table 1. We thus conclude that this effect is an evidence that LLA

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**Table 1.** The burst sample and its main characteristics (see text). The spectral and temporal indexes for GRBs before August 2006 are taken from V.(10$^{21}$ A$^0.071$ 1.73 0.10 0.061 0.38 1.10±0.7 55±21 0.13±0.2×10$^{-3}$ 55±21 18 (11), (13), (37) Gendre et al. (2008). Ulanov et al. (2005); (15) Amati et al. (2009); (17) in this work; (18) Cabrera et al. (2008); (19) Sakamoto et al. (2011); (20) Cano (2013); (11) Michalowski et al. (2012); (12) Campana et al. (2011); for $E_p$ values: (13) Pian et al. (1999); (14) Ulanov et al. (2005); (15) Amati et al. (2009); (17) in this work; (18) Cabrera et al. (2008); (19) Sakamoto et al. (2011); (20) Canampa et al. (2006); (21) Amati et al. (2007); (22) Bissaldi et al. (2008); (23) Starling et al. (2011); (24) Bhat et al. (2011); (25) Melandri et al. (2012)

**Fig. 6.** Distribution of the decay index (left) and spectral index (right) for the LLA GRBs sample (blue) compared to the reference sample (red).

**3.4. Prompt phase**

We also investigated the prompt properties of the LLA GRBs. For this purpose, as the BAT bandwidth is narrow, we used whenever possible the data from *Fermi* GBM. For events seen by Konus-Wind or BeppoSAX, we used previously published results. About half of the events have a firm measurement of the prompt parameters, the other half presenting upper and lower limits. We corrected for the cosmological redshift the values of $E_p$, obtaining the intrinsic $E_{p,i}$ values. These values cluster broadly within the 40–200 keV range.

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**Note: for $A_v$ values:** (1) Savaglio et al. (2009); (2) Pelizzizz et al. (2006); (3) Zafar et al. (2011); (4) Schady et al. (2012); (5) Kann et al. (2010); (6) Perley et al. (2013); (7) Greiner et al. (2010); (8) Starling et al. (2010); (9) Marshall et al. (2011); (10) Cano (2013); (11) Michalowski et al. (2012); (12) Campana et al. (2011); for $E_{iso}$ & $E_{p,i}$ values: (13) Pian et al. (1999); (14) Ulanov et al. (2005); (15) Amati et al. (2009); (17) in this work; (18) Cabrera et al. (2008); (19) Sakamoto et al. (2011); (20) Campana et al. (2006); (21) Amati et al. (2007); (22) Bissaldi et al. (2008); (23) Starling et al. (2011); (24) Bhat et al. (2011); (25) Melandri et al. (2012)
4. Discussion

4.1. Distance of the sample

As noted by previous authors (e.g. Watson et al. 2004; Guetta & Della Valle 2007; Daigne & Mochkovitch 2007; Imerito et al. 2008), faint GRBs cannot be detected at large distance, and, by definition, all LLA GRBs have a faint luminosity afterglow. We are thus missing distant LLA GRBs, as one could expect from the redshift distribution.

On the other hand, can we consider that all bursts with a faint afterglow are LLA GRBs, and thus that our sample is not complete?
4.2. Geometry and environment of the burst

Most of the sources can be explained by both a wind environment and a constant ISM. As shown below, many of these sources are associated with SNe (see Table 3). This association would point towards a wind environment (Chevalier et al. 2004). However, as shown by Gendre et al. (2007), the termination shock can lie very nearby to the star, and we cannot conclude firmly on the surrounding medium.

One source deserves a more careful study: GRB 120729A. This event can be accounted for by the closure relation of a jet. There is also a hint of achromaticity, as a break is seen both in X-ray and in optical around the same time (Maselli et al. 2012; D’Avanzo et al. 2012b). This supports the interpretation of a jet effect.

The opening angle is given by Levinson & Eichler (2005) who extended the work of Sari et al. (1999b) to account for the radiation efficiency of the prompt phase:

$$\theta(t_b, E_{iso}) = 0.161 \left( \frac{I_{iso}}{1 + z} \right)^{3/8} \eta_7^{1/8} \left( \frac{\eta_7}{E_{iso,52}} \right)^{1/8},$$

where the standard values for the number density of the medium $n = 1 \text{ cm}^{-3}$ and the radiative efficiency $\eta_7 = 0.2$ are used. We get $\theta = 2.7^\circ$.

From the post jet-break part of the light curve, we derive $p = 2.8 \pm 0.2$. This value is not compatible with both the spectral and temporal decay indexes ($0.74 \pm 0.072$ and $1.08 \pm 0.03$ respectively) of the pre-break part of the light curve. Only the spectral index is marginally consistent with this value of $p$, assuming $\nu_m < \nu_c < \nu_r$ and an ISM. The temporal decay is too flat (we expect a value of at least 1.5). In order to reconcile all of these facts, we need to involve some late time energy injection to flatten the light-curve (Hascoet et al. 2014). This energy injection needs to be present during the pre-break part of the light curve, but should stop during the post-break part. We note that the sampling of the X-ray light curve is not good during the jet break and allows for some non-simultaneity.

A similar argument can be drawn for GRB 060614, which may also be compatible with a jet, according to the closure relations. This burst also displays an achromatic break (around 36.6 ks) in X-ray, optical and UV (Mangano et al. 2007). However, before the jet, this burst features a plateau phase and not a standard afterglow. This is somewhat unusual for a GRB, and would request energy injection fine tuned in order to stop at the moment of the jet break. We note in addition that GRB 060614 has been proposed to be a short GRB with an extended emission (Zhang et al. 2007), making this event clearly odd in our sample. The explanation of why the energy injection would stop at the same time than the jet break is beyond the scope of this paper. In any cases, if we assume the presence of a jet, the corresponding jet opening angle is $6.3^\circ$.

Several authors (Yamazaki et al. 2003; Ramirez-Ruiz et al. 2005; Daigne & Mochkovitch 2007, e.g.) have tried to explain the properties of some of these events based on the jet properties (aperture angle, viewing angle). From our findings, when we do have a measurement of the jet aperture it is similar to the one of normal IGRBs (Ghisellini 2012; $\theta = 4.7 \pm 2.3^\circ$), and there is no hint of large off-axis viewing. The typical LLA GRB should have a jet not very different from the one of normal IGRBs.

4.3. Microphysics of the fireball

The spectral and temporal properties, once merged into the closure relations (see Fig. 7), can indicate the position of the cooling frequency and thus give some insight into the parameters of the fireball. For LLA GRBs, we have two possibilities: either we cannot conclude, or the X-ray band is located below the cooling
frequency. In the former case, this is just due to the uncertainties of the measurement. In the latter, this is not common: indeed, most late GRB afterglows are compatible with the X-ray band located above the cooling frequency (Gendre et al. 2006; De Pasquale et al. 2006). We insist here on the fact that this measure is time dependent, as shown in Gendre et al. (2006), and that the comparison need to be done with consistent data.

In the case of an homogeneous interstellar medium (ISM), the formula of the cooling frequency is (Panaitescu & Kumar 2000):

\[ \nu_c = 3.7 \times 10^{14} E^{1/2}_{53} n^{-1} (Y + 1)^{-1} \epsilon^{-3/2}_{B,2} \frac{d}{T_d^{1/2}} \text{Hz}, \]  

(3)

where \( E_{53} \) is the isotropic energy in units of \( 10^{53} \) ergs, \( \epsilon_{B,2} \) is units of \( 10^{-2} \), \( n \) is the number density of the medium in the units of \( \text{cm}^{-3} \), \( Y \) is the Compton parameter, \( \epsilon_{B,2} \) is the fraction of internal energy of magnetic field, \( T_d \) is the time expressed in days after the burst.

Instead in the case of a wind medium, the cooling frequency reads

\[ \nu_c = 3.5 \times 10^{14} E^{1/2}_{53} A_v^{-2} (Y + 1)^{-1} \epsilon^{-3/2}_{B,2} T_d^{1/2} \text{Hz}, \]  

(4)

where \( A_v \) is the number density in the wind.

For those bursts where we can conclude on the position of the cooling frequency, we can then insert the numbers to have an idea of the constraints on the model. We start by assuming that the fireball expands in the ISM. The XRT band ranges from \( 7.2 \times 10^{16} \text{Hz} \) to \( 2.4 \times 10^{18} \text{Hz} \) respectively. We however assume that \( \nu_c \) is above \( 3.7 \times 10^{18} \text{Hz} \) (i.e. slightly above the X-ray band) for simplicity. Equation 3 simplifies to:

\[ 10^{-4} E^{-1/2}_{53} \epsilon^{-3/2}_{B,2} < 1, \]  

(5)

when assuming the standard density \( n = 1 \text{cm}^{-3} \), the Compton parameter \( Y \ll 1 \) and considering the observation time of 1 day. Taking the lowest \( E_{53} \) measured (in order to have the stringent constraint), i.e. \( 10^{-5} \) (value of \( E_{53} \) for GRB 980425), we obtain:

\[ \epsilon_{B,2} > 0.1, \]  

which is not really constraining, as typical values of \( \epsilon_{B,2} \) should be of the order of 1 for IGRBs.

The situation is similar when assuming a wind medium, for which Eq. 4 simplifies to:

\[ 10^{-4} E^{-1/2}_{53} \epsilon^{-3/2}_{B,2} < 1, \]  

(6)

when assuming a standard density and a Compton parameter, and considering the observation time. Using the same method, but this time using the largest value of \( E_{53} \) (again in order to have the stringent constraint), we obtain \( \epsilon_{B,2} > 0.0012 \). Again, the magnetic energy of the fireball seems not to explain the unusual position of the cooling frequency.

We thus conclude that, under both hypotheses, the uncommon position of the cooling frequency for LLA GRBs compared to normal IGRBs is due to the small energy of the fireball rather than the magnetic energy of the fireball.

4.4. Prompt properties of LLA GRBs

In Fig. 8 we clearly see that all the outliers of the Amati relation belong to the LLA GRB sample. Several explanations have been proposed to explain these events (see Amati 2006; Amati et al. 2007 and reference therein for details): GRB 060505 may be a short GRB (as its location in the \( E_{p,j} - E_{iso} \) plane may suggest); the \( E_{p,j} \) value of GRB 061021 refers to the first hard pulse, while a soft tail is present in this burst (so the true \( E_{p,j} \) may be lower); GRB 031203 may be much softer than measured by INTEGRAL/ISGRI as supported by dust echo measured by XMM.

We can indeed see that the outliers are all located in the left part of the \( E_{p,j} - E_{iso} \) plane. In this part of the diagram, the usual gamma-ray instruments are not well suited to measure the prompt properties. For instance, the BAT measurements of GRB 060218 (Sakamoto et al. 2006) would have make this event more similar to GRB 980425, i.e. a clear outliers. It is its simultaneous observation by BAT and XRT that makes it compatible with the Amati relation. One may thus imagine that this conclusion may hold for all outliers. We note however that the prompt phase of a GRB usually shows a hard-to-soft spectral variation (e.g. Mészáros 2006) and that the prompt emission of GRB 060218 lasted significantly longer than other bursts: it is not sure that a measurement consistent with the ones done at the BeppoSAX epoch (i.e. time averaged over the complete prompt emission) would lead to a similar conclusion.

On the other hand, GRB 980425, GRB 060505 and (marginally) GRB 050826 are not compatible at all with the Amati relation. If we assume that these measurements are correct, then the best fit relation in the \( E_{p,j} - E_{iso} \) plane changes dramatically, being far more flatter.

A flatter Amati relation has been foreseen as early as 2003 (Yamazaki et al. 2003), using GRBs seen off-axis. For completeness, we also note that a similar explanation hold in case of the cannonball model (Dado & Dar 2005). Being seen off-axis, these events are expected to be less luminous than normal IGRBs even during the afterglow (see e.g. D’Alessio et al. 2006). A balance need however to be made between this argument and the fact that the events are detected: once seen off-axis, the luminosity of the burst decrease very fast with the off-axis angle. The simple fact that these events are detected means that they are not at a very large off-axis angle, but should rather be considered slightly off-axis.

Also, as already indicated, there was no a-priori reason why the LLA GRBs have a low \( E_{iso} \) (and thus a low prompt luminosity). If it is known that the prompt and afterglow luminosities are linked together (De Pasquale et al. 2006; Gehrels et al. 2008; Evans et al. 2009), this result holds for normal IGRBs and should not considered as obvious for LLA GRBs. We can confirm it also holds for this class of events.

4.5. LLA GRBs and supernovae

Nine LLA GRBs are firmly associated to SNe by spectral and photometric optical observations. They are listed in Table 3 together with the other solid associations.

In our sample, GRB 060505 (Haslip et al. 2006) and GRB 060614 (Fynbo et al. 2006; Della Valle 2007; Gal-Yam et al. 2006) are firmly not associated to SNe. Because of their close distance, any SNe would have been detected, and thus these non associations are significant. This may strengthen the conclusion that these two events are two short bursts, or at least two events not related to a normal collapsar. From our criteria, these events are not short, and thus clearly belong to the LLA GRB subclass.
We can then conclude that at least some of these events can be explained by a different kind of progenitor compared to normal IGRBs.

We also note that a large fraction of the GRB-SNe associations (64%) belong to the LLA GRBs sample. The positive associations include several well known events, such as GRB 980425/SN1998bw, GRB 031203/SN2003bw, and GRB 060218/SN2006aj. We stress that this can lead to some problems, as GRB 980425/SN1998bw is commonly used as template for light curves and spectra when looking for a SNe within the dataset of a given GRB. As discussed above LLA GRBs progenitors may differ from normal IGRB ones, which also applies to the associated supernovae. It is thus more accurate and safe to use as template GRB 030329/SN2003dh for normal IGRBs.

5. Conclusions

As already noted all papers published so far are based on the observed properties of singular faint events, or in some rare cases, two GRBs. GRB 980425-like bursts are faint in their prompt phase and cannot be detected at large distance; in addition they are not compatible with the Amati relation linking $E_{\text{iso}}$ to $E_P$. However, this does not extend to all bursts with prompt low luminosity that are outliers of the Amati relation. As an example, GRB 060218 does follow this relation, despite being faint in its prompt phase. In order to have the global answer, one needs to perform the study on a statistically significant sample of events, and this has not been done so far to our knowledge.

Here we have based our study and selected the sample on the afterglow properties, after the plateau phase, alone. The fact that this made incidentally entering some GRBs with a low-luminosity prompt was therefore not pre-supposed. This approach allows us to build a large sample, allowing for statistical studies and deriving global conclusions.

We find that LLA GRBs are on average closer than normal IGRBs. Both $A_P$ and $N_P$ of LLAs are similar to those of normal IGRBs. Most LLA GRBs are consistent with the closure relations expected by the fireball model. The few outliers can be accounted for by an early jet break. We show evidences that the events in our LLA sample are also intrinsically fainter during their prompt phase, reinforcing the evidence for a different population. Actually, some events do not follow at all the $E_{\text{iso}}$ - $E_P$ relation.

We have shown that in order to explain all of these properties, we can involve either the geometry of the bursts or a different kind of progenitors. In the former hypothesis, the bursts would be seen slightly off-axis in order to explain the low energy budget observed in these events. In the latter, one could imagine that the progenitor provides less mater for the accretion, thus diminishing the energetic budget at start.

The LLA GRBs sample includes a significant fraction of the supernovae associated with GRBs (64%), including the best known associations. This means that the conclusion drawn on the general GRB-SN association is based on a sub-sample of the low-luminosity population (the LLA GRBs) that might not be representative. We stress the need to confirm this point and the previous work on GRB-SN associations using different spectral and light curve templates, for instance those of GRB 030329/SN2003dh.

Acknowledgements. We thank Cristiano Guidorzi, at University of Ferrara, for providing help during the analysis of the BAT spectra. This paper is under the auspices of the FIGARONet collaborative network, supported by the Agence Nationale de la Recherche, program ANR-14-CE33. We used the data supplied by the UK Swift Science Data Center at the University of Leicester. H. Dereli is supported by the Erasmus Mundus Joint Doctorate Program by Grant Number 2011-1640 from the EACEA of the European Commission.

References

Amati, L., 2006, MNRAS, 372, 233
Amati, L., Della Valle, M., Frongia, P., et al. 2007, A&A, 463, 913
Amati, L., Frongia, P., & Guidorzi, C., 2009, A&A, 508, 173
Ade, P. A. R., Aghanim, N., Alves, M. I. R., et al. 2013, astro-ph/1303.5062
Barniol-Duran et al. 2015, MNRAS, 449, 417
Barthelmy, S. D., Baumgartner, W. H., Cummings, J. R., et al. 2012, GCN Circ., 13246
Bhat, P. N., 2011, GCN Circ., 11543
Bissaldi, E., McBreen, S., & Connaughton, V., 2008, GCN Circ., 8369
Bloom, J. S., Kulkarni, S. R., Price, P. A., et al. 2002, ApJ, 572, L45
Blustin, A. J., Band, D., Barthelmy, S., et al. 2006, ApJ, 637, 901
Boer, M., Gendre, B., & Stratta, G., 2014, ApJ, in press
Cabrera, G. F., Casassus, S., & Hitschfeld, N., 2008, ApJ, 672, 1272
Campana, S., Mangano, V., Blustin, A. J., et al. 2006, Nature, 442, 1008
Campana, S., Lodato, G., & D’Avanzo, P., et al. 2011, Nature, 488, 69
Cano, Z., 2013, MNRAS, 434, 1098
Chevalier, R. A., & Li, Z. Y., 2000, ApJ, 536, 195
Chevalier, R. A., Li, Z. Y., & Fransson, C., 2004, ApJ, 606, 369
Chornock, R., Soderberg, A. M., Foley, R. J., et al. 2010, IAU, 2288
Cobb, B. E., Bailyn, C. D., van Dokkum, P. G., & Natarajan, P., 2006, ApJ, 645, L113
Table 3. The table of GRB-SN associations. The $L_{iso}$ values are calculated from the $E_{iso}$ values which are given in the Table 1.

| GRB name | redshift | SN identification | SN name | SN type | Host type | LLA | GRB | $L_{iso}$ (10^{48} erg s^{-1}) | Ref. |
|----------|----------|--------------------|---------|---------|-----------|-----|-----|---------------------------|------|
| GRB 990425 | 0.0085 | spectral | SN1998bw | BL-Ic | dwarf spiral | yes | 0.033 | (1) |
| GRB 011121 | 0.36 | spectral | SN2001ke | In | N/A | yes | 387 | (2) |
| GRB 021211 | 1.01 | spectral | SN2002ht | ~Ic | N/A | no | 969 | (3, 4, 5) |
| GRB 030329 | 0.168 | spectral | SN2003dh | BL-Ic | N/A | no | 75 | (6, 7, 8) |
| GRB 031020 | 0.105 | spectral | SN2003bw | Irf | Wolf-Rayet | yes | 0.56 | (9, 10) |
| GRB 050525 | 0.606 | spectral | SN2005uc | ~Ic | N/A | yes | 417 | (11, 12) |
| GRB 060218 | 0.0331 | spectral | SN2006aj | BL-B/c | dwarf Irf | yes | 0.02 | (13, 14, 15) |
| GRB 080107 | 0.5295 | spectral | SN2008bw | Ic | N/A | no | 0.30 | (16, 17) |
| GRB 091127 | 0.49 | spectral | SN2009hz | BL-Ic | N/A | no | 345 | (18, 19) |
| GRB 100314D | 0.059 | spectral | SN2010bh | BL-Ic | Spiral blue | yes | 0.056 | (20, 21) |
| GRB 101210B | 0.55 | spectral | SN2010ma | Ic | N/A | no | 225 | (22, 23) |
| GRB 120422A | 0.283 | spectral | SN2012bz | Ibc | N/A | yes | 0.44 | (24, 25) |
| GRB 120714B | 0.394 | spectral | SN2012Ib | Ic | no identification | yes | 0.7 | (26, 27) |
| GRB 130305C | 0.597 | spectral | SN2013er | Ic | N/A | no | 35 | (28, 29) |

Note: for GRB-SN associations: (1) Galama et al. [1998]; (2) Bloom et al. [2002]; (3) Crew et al. [2002]; (4) Della Valle et al. [2003]; (5) Vreeswijk et al. [2003]; (6) Golenetskii et al. [2003]; (7) Soderberg et al. [2003]; (8) Soderberg et al. [2003]; (9) Soderberg et al. [2003]; (10) Tagliaferri et al. [2004]; (11) Della Valle et al. [2006]; (12) Blustin et al. [2006]; (13) Cobb et al. [2006]; (14) Campana et al. [2006]; (15) Soderberg et al. [2006]; (16) Soderberg et al. [2008]; (17) Markwardt et al. [2008]; (18) Cobb et al. [2009]; (19) Wilson-Hodge & Preece [2009]; (20) Chornock et al. [2010]; (21) Sakamoto et al. [2010]; (22) Van Der Horst et al. [2010]; (23) Sparre et al. [2011]; (24) Melandri et al. [2012]; (25) Barthelmy et al. [2012]; (26) Klose et al. [2012]; (27) Cummings et al. [2012]; (28) de Ugarte Postigo et al. [2013]; (29) Younes et al. [2013];
Virgili, F.J., Liang, E.W., & Zhang, B., 2009, MNRAS, 392, 91
Vreeswijk, P., Fruchter, A., Hjorth, J., & Kouveliotou, C., 2003, GCN Circ., 1785
Watson, D., Hjorth, J., Levan, A., et al. 2004, ApJ, 605, L101
Willingale, R., O’Brien, P. T., Osborne, J. P., et al. 2007, ApJ, 662, 1093
Wilson-Hodge, C. A., & Preece, R.D., 2009, GCN Circ., 10204
Yamazaki, R., Yonetoku, D., & Nakamura, T., 2003, ApJ, 594, L79
Younes, G., & Bhat, P. N., 2013, GCN Circ., 14219
Zafar, T., Watson, D., Fynbo, J. P. U., et al. 2011, A&A, 532, A143
Zhang, B., Fan, Y. Z., Dyks, J., et al. 2006, ApJ, 642, 354
Zhang, B., Zhang, B. B., Liang, E. W., Gehrels, N., Burrows, D. N.; & Meszaros, P., 2007, ApJ, 655, L25
Zhang, B., & Meszáros, P., 2008, IJMP, 7, 42
Zhang, B. B., Zhang, B., Murase, K., Connaughton, & V., Briggs, M. S., 2014, ApJ, 787, 66