

# Properties of Low-Luminosity Afterglow GRBs

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The Low Luminosity Afterglow (LLA) gamma-ray bursts (GRBs) are characterized by their very intrinsically faint X-ray afterglows. They represent 12% of all long (of duration more than 2 s) GRBs (IGRBs) with a measured redshift. They are on average closer than normal IGRBs and their distribution is not affected by the gas and dust from the Milky Way and host galaxies. Additionally, the angle of observation is aligned with the jet's direction, has proven by founding the jet breaks in some cases.

In this work, we studied the host galaxy properties (mass, metallicity, star formation rate) of LLA GRBs. These properties were compared to those of normal IGRBs and we found that they are similar. We also showed that the prompt properties of LLA GRBs are somewhat different from that of other IGRBs, as shown by their position in the Amati relation. We computed the volume density of LLA GRBs and found that they have higher rate density compare to normal IGRBs.

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## 1. Introduction

Long Gamma-Ray Burst are thought to be the result of a cataclysmic collapse of a massive star [1]. However, different sub-classes of long GRBs (under-luminous bursts [2, 3], ultra-long GRBs [4], dark bursts, X-ray flashes) were proposed in the literature. In 2008, Gendre et al. [5] showed the existence of a wide dispersion of the afterglow luminosity of long GRBs (from the brightest to the faintest ones). In this work, we have studied the faintest part of this distribution and we have chosen 31 GRBs hereafter designed by Low-Luminosity Afterglow (LLA) GRBs [6] by considering all long bursts with a measured redshift, observed before February 15<sup>th</sup>, 2013 (corresponding to 254 bursts), by studying their X-ray afterglows after rescaling all the fluxes at  $z = 1$  and applying a flux threshold of  $10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$  at one day (which also corresponds to the lowest afterglow luminosity in D’Avanzo et al. (2012) [7]) and by applying a template power-law with decay index 1.2 (corresponding to the typical value expected with  $p \sim 2.3$  where  $p$  is the power law index of the accelerated electrons in the cases of interstellar circumburst medium) in the flux-time plane.

LLA GRBs consist of 12% of LGRBs with a measured redshift. Their distribution is not affected by the gas and dust from the Milky Way and their host galaxies more than normal LGRBs [6]. Most of the LLA GRBs are characterized by a fireball in the slow-cooling state expanding in the constant interstellar medium (ISM). The few outliers can be interpreted by a fireball expanding in a wind-like medium *e.g.* GRB 011121 or by the emission of a jet. We found jet break for GRB 060614 and GRB 120729A.

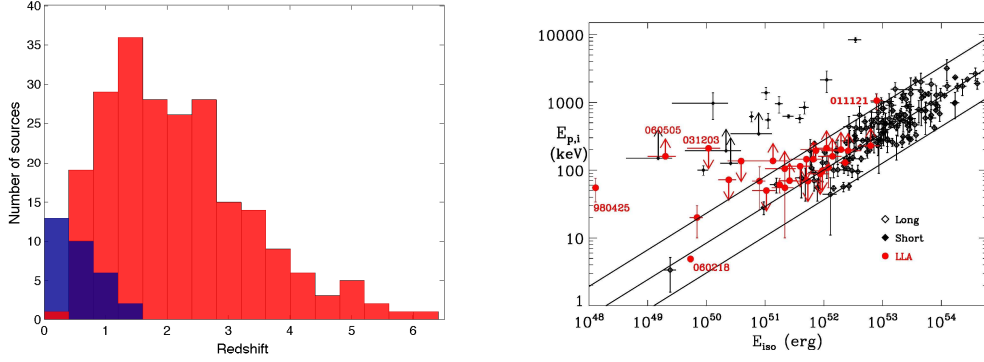
In this work, we used a standard flat  $\Lambda$ CDM model with  $\Omega_m = 0.3$  and  $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

## 2. Redshift Distributions

There is a significant difference between the redshift distributions of LLA GRBs and normal LGRBs as seen in Figure 1a). This is also confirmed by the result of the Kolmogorov-Smirnov test show that the probability for two distributions to be based on the same population is  $1.1 \times 10^{-14}$ . LLA GRBs are on average closer than normal LGRBs. Obviously, the LLA GRB distribution is strongly biased against high redshifts. In order to have a fairer comparison, we restricted both distributions to  $z < 1$ , redshift for which we assumed that all LLA GRBs would be detected. Then we applied the Kolmogorov-Smirnov test. It shows that the probability for two distributions to be based on the same population is  $9.4 \times 10^{-4}$ . The lack of observations of intrinsically faint events at large distances can be explained by selection effects, however, there is no clue for the lack of intrinsically bright events in the local Universe.

## 3. Amati correlation: prompt properties of LLA GRBs

We also investigated the prompt properties of LLA GRBs. As seen in Figure 1b), all outliers to the Amati relation [8] are in this sample. It is also found that the  $E_{p,i}$  values cluster broadly within the 40-200 keV range which can be a bias effect introduced by instrument. However, the situation is different with  $E_{iso}$ . There is a clear shift in the  $E_{iso}$  axis with respect to most normal LGRBs. We conclude that LLA GRBs are less energetic during their prompt phase compared to normal LGRBs. Because of the correlation between  $L_{prompt}$  and  $L_{afterglow}$  [7], this is not surprising.

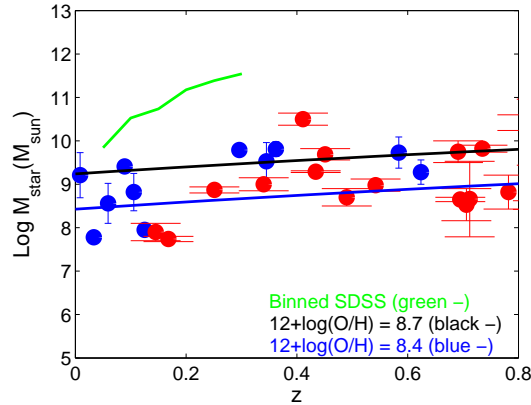


**Figure 1:** a) Redshift distribution of LLA GRBs (blue) compared to that of normal IGRBs (red). b) Location in the  $E_{p,i}$  -  $E_{iso}$  plane of LLA GRBs compared to both short and normal IGRBs.

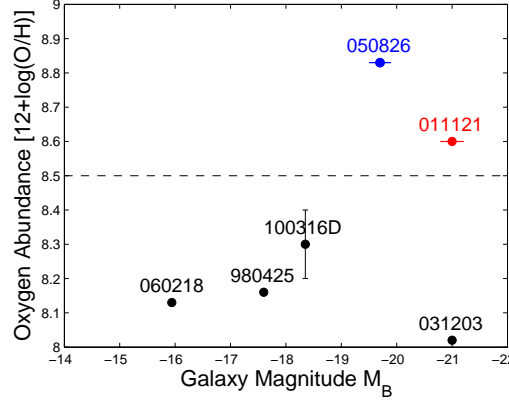
#### 4. Host properties of LLA GRBs

The differences between the host galaxies of LLA GRBs and those of normal IGRBs are very small.

**Mass and Metallicity:** The mean value of the host masses is  $10^{9.5} M_{\odot}$  for normal IGRBs, while it is slightly smaller for LLA GRBs, the mean value being  $10^{9.1} M_{\odot}$ . When we compared the host galaxies of the three samples (LLA GRBs, normal IGRBs and SDSS) at a given metallicity, we found that host galaxies of GRBs have larger masses than those in the SDSS survey at a constant metallicity level, and that the normal IGRB host masses are slightly larger than the LLA GRB host masses at a constant metallicity level. This is seen in Figure 2.

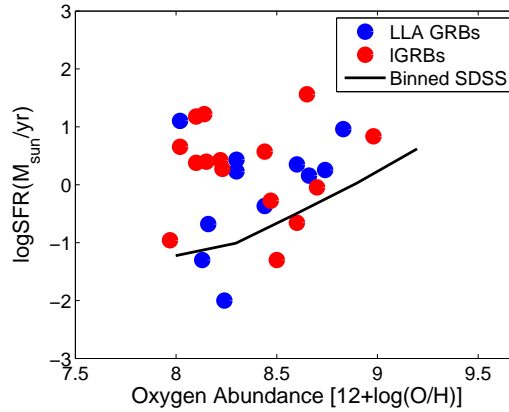


**Figure 2:** Mass-redshift distributions of LLA GRBs (blue filled circles) and IGRBs (red filled circles) host galaxies. The solid lines represent the mean value of the metallicity  $12 + \log(\text{O}/\text{H})_{\text{KK04}} = 8.7$  (black) of SDSS galaxies [9] and the mean value of the metallicity  $12 + \log(\text{O}/\text{H})_{\text{KK04}} = 8.4$  (blue) of LLA GRB hosts. The green solid line represents the average binned mass of SDSS galaxies [10].



**Figure 3:** The distribution of metallicity-B magnitude of the host of LLA GRBs. The horizontal dashed line represents the cut-off limit of metallicity at  $12 + \log(\text{O}/\text{H})_{\text{KD02}} = 8.5$  [11]. GRBs associated to broad-line Ic SNe are presented by black points while GRB 011121 (associated to a type IIIn SN) and GRB 050826 (no association to SN) are presented by red and blue points respectively.

**Metallicity and Brightness:** The comparison between the host galaxy properties of LLA GRBs and those of normal IGRBs is difficult since few magnitude values of the host galaxies were obtained. However, we found interesting that host galaxies of GRBs associated to type Ic SN have lower metallicity than that of GRBs without SN. In addition, the metallicity of the host of GRB 011121 associated to a type IIIn SN, is also above the threshold [11] see Figure 3.



**Figure 4:** The SFR-metallicity distribution of LLA GRBs and IGRBs host galaxies.

**Star Formation Rate and Metallicity:** It is clearly seen in Figure 4 that the SFR of GRB hosts is larger compared to that of SDSS galaxies [10]. Additionally, the mean values for the star formation rate are  $2.94 M_{\odot} \text{ yr}^{-1}$  for LLA GRBs and  $6.29 M_{\odot} \text{ yr}^{-1}$  for normal IGRBs. The reason for this difference is that since less stars are formed as a whole, less very massive stars are formed as well, thus limiting the number of normal IGRBs. Thus, the possible progenitor of a LLA GRB would be less massive, and as a result the GRB less energetic.

## 5. Rate Density of LLA GRBs

The rate density is calculated by considering only the LLA GRBs observed by the *Swift* satellite:

$$R_{GRB} = \frac{1}{V_{max}} \frac{1}{S_{cov}} \frac{1}{T} B(\theta) \frac{1}{\eta_z}, \quad (5.1)$$

where  $S_{cov}$  is the fractional sky coverage (which is 0.17 for *Swift*),  $T$  is the time during which the satellite was observing (6.4 years for LLA GRBs, which takes into account when *Swift* was not observing),  $V_{max}$  is the maximum volume [12],  $B(\theta) = [1 - \cos(\theta)]^{-1}$  and  $\theta$  is the beaming angle. The efficiency of measuring the redshift  $\eta_z$  is 0.3 for IGRBs observed by the *Swift* satellite.

**Table 1:** The observed (considering  $V_{max}$ ,  $S_{cov}$ ,  $T$  and  $\eta_z$ ) and intrinsic (also considering  $B(\theta)$ ) total rate density are computed by using the parameters of the 25 LLA GRBs observed by *Swift*.

$R_{LLA\ GRB, obs}$ $\text{Gpc}^{-3} \text{ yr}^{-1}$	$R_{LLA\ GRB, int}$ $\text{Gpc}^{-3} \text{ yr}^{-1}$
358,83	285316.04

### 5.1 Comparison with long GRBs

We found out that the rate density of LLA GRBs is much higher than that of IGRBs ( $1 \text{ Gpc}^{-3} \text{ yr}^{-1}$  [3]), see Table 1. However, the rate density in our computation is dominated by GRB 060218 and GRB 100316D (observed rate densities  $212 \text{ Gpc}^{-3} \text{ yr}^{-1}$  and  $145.6 \text{ Gpc}^{-3} \text{ yr}^{-1}$  respectively). This is because these two bursts are extremely close ( $z < 0.1$ ) and their maximum fluxes are below the theoretical flux detection threshold. Interestingly, if we remove these two bursts from the computation, we found that the local rate density of LLA GRBs ( $1.23 \text{ Gpc}^{-3} \text{ yr}^{-1}$ ) is compatible to that of normal IGRBs.

### 5.2 Comparison with short GRBs

Another comparison is performed between LLA GRBs and short bursts. This is important as the position of some LLA GRBs in the  $E_p - E_{iso}$  plane is compatible with the position of short GRBs. The total rate of short GRBs was estimated to be  $8_{-3}^{+5} \text{ Gpc}^{-3} \text{ yr}^{-1}$  if the emission is not collimated in a jet, and  $1100_{-470}^{+700} \text{ Gpc}^{-3} \text{ yr}^{-1}$  if it is collimated in a jet [12]. Thus, we can conclude that LLA GRBs (except GRB 060505) which are at the position of short GRBs in the  $E_p - E_{iso}$  plane cannot be considered as short bursts with a duration larger than 2 s, as their individual rate is too small compared to that of short GRBs and in addition as many of the LLA GRBs have an observed association to SN. So, performing the computation for GRB 060505 only gives a observed rate of  $0.91 \text{ Gpc}^{-3} \text{ yr}^{-1}$ , comparable to the average rate ( $1 \text{ Gpc}^{-3} \text{ yr}^{-1}$ ) of individual short bursts and this GRB has no known association to a SN.

## 6. Conclusions

LLA GRBs are on average closer and less energetic than normal IGRBs. In addition, they have larger rate density than that of normal IGRBs. However, the differences in the host galaxy properties are small, but it might be the result of a lack of statistics. All these elements put together might indicate a different progenitor for LLA GRBs.

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