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Investigating High Redshift Short GRBs: Signatures of Collapsars?

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Abstract

The conventional classification of Gamma-Ray Bursts (GRBs) as short or long bursts based on their duration is widely accepted as arising from different progenitor sources identified as compact object mergers and collapsars, respectively. However, recent observational shreds of evidence challenged this view, with signatures of collapsars in short GRBs and mergers in long GRBs. We conduct a comparative analysis of the characteristics of short and long GRBs, both at low and high redshifts, taking into account the locations and environments of their host galaxies. Our analysis suggests that some short GRBs at higher redshifts exhibit features similar to long GRBs, indicating a possible collapsar origin. Further investigation, utilizing multi-messenger observations, could provide a resolution to this issue.

Keywords: GRB, Classification, Progenitors, Collapsars, Mergers

1. Introduction

The bimodality in the duration of GRBs suggested two broad classes as long and short determined by the T_{90} duration (the time interval of integrated counts between 5% to 95%) with a boundary at 2 seconds (Kouveliotou et al., 1993). The long-duration GRBs, with $T_{90} > 2\,\mathrm{s}$, were postulated to stem from the death of the massive stars (Woosley, 1993; Mészáros, 2006), while the short-duration, with $T_{90} \leq 2\,\mathrm{s}$, were believed to stem from mergers involving compact objects (Paczynski, 1986; Meszaros and Rees, 1992). Multi-wavelength observations of GRBs provided evidence in support of these predictions, as several long GRBs have been discovered to be linked with Type Ic supernovae (Woosley, 1993; MacFadyen and Woosley, 1999; Hjorth et al., 2003; Woosley and Bloom, 2006; Cano et al., 2017), and the origin of short-duration GRBs from compact object mergers is supported by the coincident discovery of GW170817/GRB 170817A and the associated kilonova AT 2017gfo (Abbott et al., 2017; Valenti et al., 2017).

The established theory of long and short GRBs origin became questionable after the detection of a supernova bump associated with a short-duration GRB in August 2020, GRB 200826A (Zhang et al., 2021; Ahumada et al., 2021; Rossi et al., 2022), and a long-duration GRB identified with a kilonova bump in December 2021, GRB 211211A (Rastinejad et al., 2022; Troja et al., 2022; Yang et al., 2022). Recently, another long GRB 230307A is found to be associated with a kilonova (Levan et al., 2023). The dichotomous separation of GRBs based on duration has been questioned time and again (Fynbo et al., 2006; Zhang et al., 2009). In the past, numerous efforts have been undertaken to create novel classification systems utilizing criteria distinct from the traditional T_{90} classification. For instance, Zhang (2006) categorized GRBs into Type I (arising from compact binary mergers) and Type II (arising from death of massive stars) groups. Bromberg et al. (2013) employed a classification based on collapsar and non-collapsar probabilities. Additionally, Minaev and Pozanenko (2020) utilized the $E_{\gamma,\mathrm{iso}}$–$E_{\mathrm{p,i}}$ correlation to divide GRBs into two distinct classes. Additional parameters such as hardness ratio, spectral lag, and variability time scales in light curves were identified to differentiate between distinct progenitors of GRBs (Fishman and Meegan, 1995; Bernardini et al., 2015; McInnes et al., 2018). However, these parameters have a significant overlap for the two classes, making classification challenging as argued by Dimple et al. (2022). Distinction between long and short GRBs still remains challenging.

The redshift distributions of long and short GRBs provide essential clues about their progenitor systems (Guetta and Piran, 2005; Berger et al., 2007; Ghirlanda et al., 2009; D'Avanzo, 2015). The median redshifts observed for long and short GRBs strongly suggest that these events originate from different types of progenitors. The higher redshift of long GRBs agrees with the predictions of rapidly evolving massive star progenitors. In contrast, the lower redshift of short GRBs matches with the longer timescales of compact object mergers (Berger et al., 2013). However, a fraction of short GRBs is found to lie at high redshifts contradicting their proposed progenitors. Given the overlap observed between the two classes, it is reasonable to investigate the properties of short and long GRBs at both low and high redshifts.

Our recent work on the comparison of low and high redshift short GRBs suggested that they could be arising from different progenitor systems (Dimple et al., 2022). We expand on this work with an updated sample and identify their position on the Amati plot (Amati, 2006) as well as compare their offset (i.e., the distance between the burst and the centre of its host galaxy) and number density (the density of the ambient medium) distributions. Both offset and number density aid in inferring the GRB progenitors. The description of the sample and comparison of the short GRB properties (Amati correlation, offset, number density, non-collapsar probability; F_{nc} and star formation rate; SFR of GRB hosts) are given in Sect. 2. The key findings are summarised in Sect. 3.

2. Are Short GRBs at High Redshift Similar to Long GRBs?

The redshift distribution (the left panel of Fig. 1) shows that short GRBs are found at significantly lower redshifts as compared to long GRBs. The sample is compiled from Jochen Greiner's long GRB table (https://www.mpe.mpg.de/~jcg/grbgen.html) with known spectro-

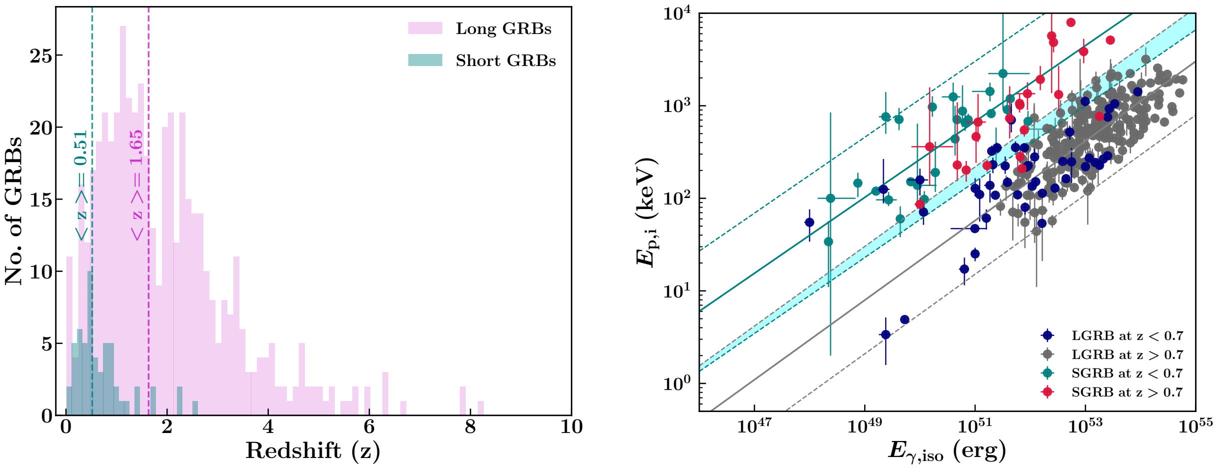

Figure 1: (*Left*) The redshift distributions of GRBs up to April 2023. Short GRBs occupy the lower end of the distribution, with a median redshift of 0.47. In contrast, long GRBs span a wider range of redshifts, with a median of 1.68. (*Right*) Short and long GRBs in the Amati correlation plane. The solid blue and grey lines in the plot depict the best-fit correlation for long and short GRBs, respectively, while the dotted lines illustrate the corresponding 2σ regions. The shaded region shows the overlapping 2σ regions between long and short GRBs. It can be observed that at redshifts $z > 0.7$, some short GRBs follow the long GRB track, while some fall within the overlapping 2σ region. Similarly, some long GRBs at lower redshifts follow the short GRB track.

scopic redshifts and is complete up to April 2023. We estimated the median redshift of short GRBs to be $z = 0.51$, much lower than the median redshift of long GRBs at $z = 1.65$, consistent with the expectations for their progenitors. However, a notable proportion of short GRBs is observed to occur at higher redshifts ($z > 0.7$). Out of these, GRBs 200826A ($z = 0.7481$; Rossi et al., 2022) and 090426 ($z = 2.609$; Antonelli et al., 2009), have been suggested to originate from collapsars rather than compact object mergers. It is crucial to investigate whether the progenitors of short GRBs at low and high redshifts differ and if the high redshift short GRB progenitors share similarities with those of long GRBs. As suggested by Berger et al. (2007) and Bromberg et al. (2013) that the short GRBs detected at higher redshifts may represent a distinct population of GRBs, our investigation explores the similarities and dissimilarities between short GRBs lying at low and high redshifts and that with long GRBs.

Since, a short GRB has been observed to be associated with supernova at a redshift of 0.7481 (GRB 200826A) and around 43% of short GRB lie at $z > 0.7$. Therefore, we have put a cut at $z = 0.7$. For this, we plot the Amati correlation and examine their offset and number density distributions, and the F_{nc} and SFR estimations of the hosts to investigate their progenitor systems.

2.1. Amati correlation

For a long time, correlations in prompt emission have been utilized to categorize GRBs. In the Amati correlation plane, which plots $E_{\gamma,\mathrm{iso}}$ against E_{p} (the peak energy in the source frame), two distinct classes of GRBs follow different tracks, and occupy different positions (Amati et al., 2002; Amati, 2006). To check the Amati correlation of GRBs lying at various redshifts, we took the isotropic and peak energy values from Minaev and Pozanenko (2020) and divided the sample according to the redshift of the data with a divider at a redshift of 0.7. Short GRBs lying at redshift > 0.7 are located on the long GRB track, while some of them are in the overlapping 2σ correlation region (cyan shaded region) between short and long GRBs, as can be noticed from the right panel of Fig. 1. Similarly, some of the long GRBs lying at lower redshifts are located on the short GRB track. The presence of short GRBs at high redshifts aligning with the long GRB track and low-redshift long GRBs falling on the short GRB track can be due to the selection effects or these GRBs originate from progenitors that differ from their identified class based on duration.

2.2. Offset distribution

The offset of a GRB from its host galaxy can provide meaningful insight into its progenitor system. Binary compact stellar remnants are expected to merge far from their birth sites due to the kicks imparted to the neutron stars during supernova explosions (Belczynski et al., 2002, 2006). As a result, GRBs arising from these progenitors are expected to have large offsets from their host galaxies (Berger et al., 2013). However, in the case of massive star collapse, GRBs are expected to occur near their birth site, likely in an active star-forming region (Fruchter et al., 2006). As a result, GRBs arising from collapsars are likely to have smaller offsets from their host galaxies which has also been confirmed observationally (Bloom et al., 2002).

Figure 2 illustrates the offset distributions of long and short GRBs using data from Blanchard et al. (2016) and Fong et al. (2022), respectively. From the left panel of the figure, we deduce that the projected offsets of short GRBs range from 0.23 to 76.19 kpc, with a median offset of approximately 9.62 kpc. This median offset is approximately six times larger than the median offset observed for long GRBs, which is approximately 1.38 kpc. The distribution of short GRBs aligns with the predictions of population synthesis models for compact object mergers, especially regarding the fraction of events displaying significant offsets. Conversely, long GRBs exhibit significantly lower offsets, consistent with the expectations of massive star progenitors exploding in close proximity to their birth site within the host galaxy.

The right panel of Fig. 2 presents the variation of offset with the redshift of GRBs. It is apparent that short GRBs at higher redshifts tend to have slightly smaller offsets compared to those at lower redshifts, although they still remain noticeably larger than the offsets observed for long GRBs. While a few short GRBs display offsets similar to those of long GRBs, the overall offset distribution strongly supports the existence of two distinct progenitor populations for long and short GRBs. Further investigation of short GRBs with lower offset values would be of great interest to understand their unique characteristics and progenitor systems.

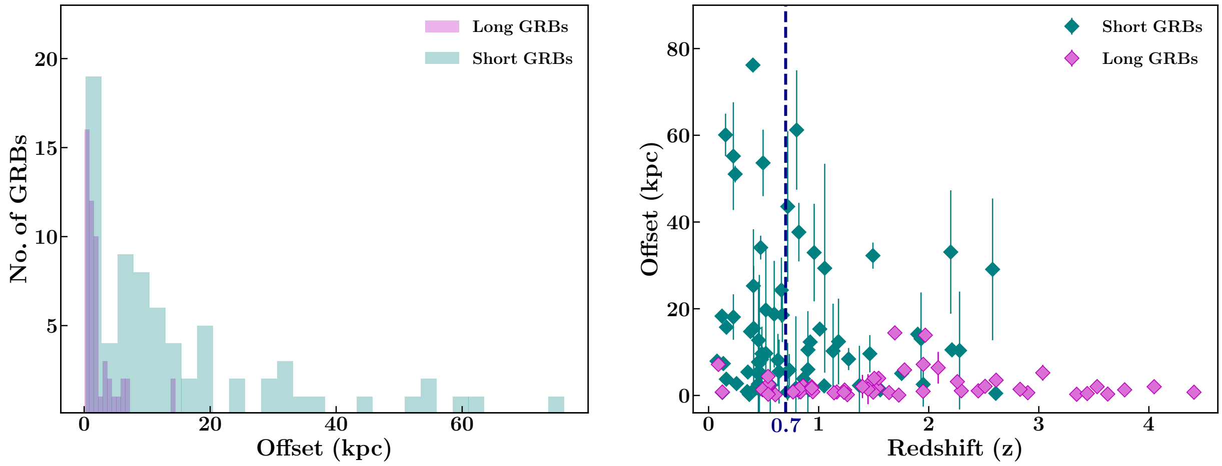

Figure 2: (*Left*) Offset distribution of GRBs. Short GRBs display a median offset of approximately 9.62 kpc, which is roughly six times larger than the median offset observed for long GRBs (1.38 kpc). (*Right*) Variation of offsets with redshifts for GRBs with a cut at a redshift of 0.7.

2.3. GRB environments: number densities

Both the progenitors (collapsars and mergers) also differ in the number densities of their environments. Long-duration GRBs are often linked to star-forming regions exhibiting high gas densities, indicating the presence of dense environments surrounding these events. Conversely, short-duration GRBs are found in low-density environments (O'Connor et al., 2020), possibly due to natal kicks that propel them into the wider interstellar medium or even the intergalactic medium (Berger et al., 2013). In order to examine the variation of number density for long and short GRBs, we utilized a sample of long GRBs from Chrimes et al. (2022) and short GRBs from Fong et al. (2015). Both the studies have estimated the environmental number densities by fitting the afterglow data with standard afterglow model (the forward-reverse shock model, Sari et al. (1998)). The results are illustrated in Fig. 3. The median number densities for long and short GRBs are 0.315 cm^{-3} and 0.0068 cm^{-3}, respectively. There is a substantial overlap observed in the number densities of long and short GRBs; however, the short GRB distribution is skewed more towards low number densities and long GRB towards high number densities. The right panel of Fig. 3 shows the variation of number densities with redshift. It can be seen that the short and long GRBs show similar trends with low redshift short GRBs typically favouring lower densities up to 10^{-5} cm^{-3}.

3. Discussions

To investigate whether long and short GRBs with known redshifts have similar progenitor systems, we compared various properties between them in detail. We located low and high redshift GRBs on the Amati plane. Overall, short and long lie on two different tracks, however, some of the GRBs show peculiarity and share a different track. Interestingly, these are high redshift short GRBs and low redshift long GRBs. Further, we found similarities between high-redshift short GRBs and long GRBs in terms of offsets and environmental densities with

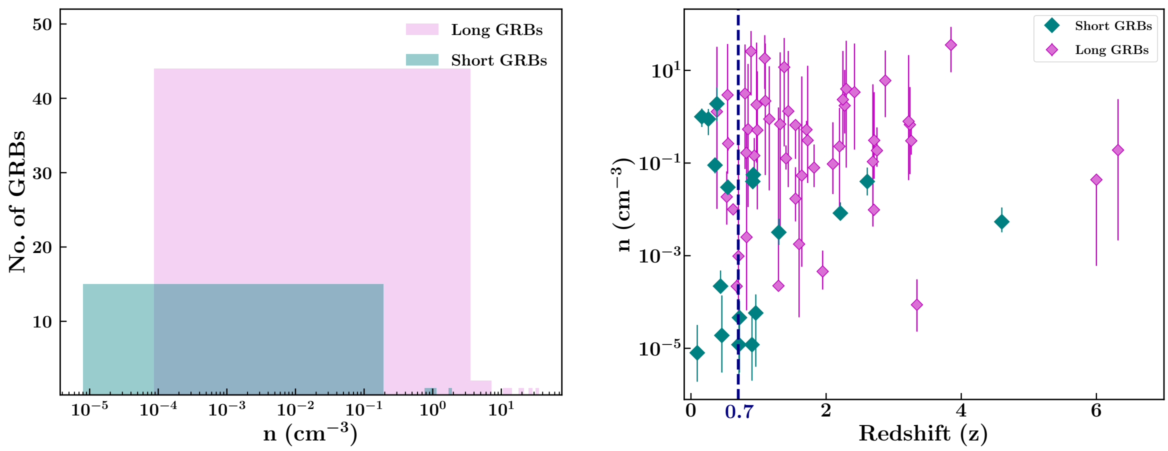

Figure 3: (*Left*) Number density distribution for long and short GRB environments. Median number densities are 0.315 cm^{-3} for long GRBs and 0.0068 cm^{-3} for short GRBs. (*Right*) Variation of the number density of GRB environments with redshift with a cut at $z = 0.7$.

redshift. Also, the low values of $F_{\rm nc}$ and high values of SFR of short GRBs support the argument that high-redshift short GRBs could have progenitors similar to those of long GRBs (Dimple et al., 2023; Dichiara et al., 2021; Bromberg et al., 2013). However, this can also be an observational bias. More studies are needed to understand better the role of redshift in GRB classification and the reliability of inferring progenitors based on empirical correlations. Future multimessenger observations, including optical and near-infrared observations, will be instrumental in detecting bumps in GRBs' light curves, which can help in identifying supernovae/kilonovae associated with collapsars/compact binary mergers. These observations, accompanied by gravitational wave detections, will provide additional information on the properties of the progenitor. In addition, machine learning algorithms play a crucial role in clustering the GRBs based on fine structures present in their light curves. Jespersen et al. (2020) and Steinhardt et al. (2023) have used t-distributed Stochastic Neighbor Embedding (t-SNE) and Uniform Manifold Approximation and Projection (UMAP), respectively, to identify clustering in the population of GRBs. Luo et al. (2022) also made use of supervised machine learning techniques to distinguish between different progenitor systems of GRBs. However, these studies focused more on the general classification of GRBs based on their light curves and did not survey any specific subpopulation, such as that of the KN-associated GRBs. Recently, Garcia-Cifuentes et al. (2023) has used t-SNE to investigate the extended emission GRBs. We employ the Principal Component Analysis (PCA) in conjunction with t-SNE and UMAP to the light curves to cluster the GRB population (Dimple et al., 2023). We will investigate the short GRBs at high redshifts using machine learning algorithms in near future.

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Further Information

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Author contributions

Toward the completion of this work, all authors have made significant contributions.

Conflicts of interest

The authors declare no conflict of interest.

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