

# Alternative statistical interpretation for the apparent plateaus in the duration distributions of gamma-ray bursts<sup>★</sup>

Joshua Alexander Osborne<sup>1</sup>, Christopher Michael Bryant<sup>1</sup>, Fatemeh Bagheri<sup>1,★★</sup>, and Amir Shahmorad<sup>1,2</sup> 

<sup>1</sup> Department of Physics, The University of Texas, Arlington, TX 76010, USA  
e-mail: [joshua.osborne@uta.edu](mailto:joshua.osborne@uta.edu); [fatemeh.bagheri@uta.edu](mailto:fatemeh.bagheri@uta.edu)

<sup>2</sup> Division of Data Science, The University of Texas, Arlington, TX 76010, USA  
e-mail: [shahmoradi@utexas.edu](mailto:shahmoradi@utexas.edu)

Received 14 November 2023 / Accepted 22 April 2024

## ABSTRACT

**Context.** The existence of a plateau in the short-duration tail of the observed distribution of cosmological long-soft gamma ray bursts (LGRBs) is posited to be the first direct evidence of collapsars. A similar plateau in the short-duration tail of the observed duration distribution of short-hard gamma ray bursts (SGRBs) has been suggested as evidence of compact binary mergers.

**Aims.** We present an equally plausible alternative interpretation for this evidence, based on a purely statistical approach.

**Methods.** Specifically, we show that the observed plateau in the short-duration tail of the duration distribution of LGRBs can naturally occur in the statistical distributions of strictly positive physical quantities, exacerbated by the effects of mixing with the duration distribution of SGRBs, observational selection effects, and data aggregation (e.g., binning) methodologies. The observed plateau in the short-duration tail of the observed distributions of SGRBs may likewise result from a combination of sample incompleteness and inhomogeneous binning of data. We further confirm the impact of these factors on the observation of a plateau in the duration distributions of GRBs through extensive numerical Monte Carlo simulations.

**Results.** This analysis corroborates and strengthens a purely statistical and sample-incompleteness interpretation of the observed plateau in the duration distribution of LGRBs and SGRBs, without invoking the physics of collapsars or jet-propagation through the stellar envelope.

**Key words.** methods: analytical – methods: data analysis – methods: statistical – astronomical databases: miscellaneous – gamma-ray burst: general

## 1. Introduction

Gamma-ray bursts (GRBs) are mainly split into two categories: long-duration GRBs (LGRBs), with  $T_{90} > 2$  s, and short-duration GRBs (SGRBs), with  $T_{90} < 2$  s (e.g., [Kouveliotou et al. 1993](#)). Specifically,  $T_{90}$  is the time it takes to receive 90% burst fluence, starting when 5% of the fluence has been observed (e.g., [Poolakkil et al. 2021](#)). Significant observational evidence over the past two decades has connected LGRBs to the death and the iron core-collapse of supermassive stars ([Fruchter et al. 2006](#); [Woosley & Bloom 2006](#)). Specifically, the leading theory points toward Wolf-Rayet stars, with masses between  $10 M_{\odot}$  and  $50 M_{\odot}$  ([Massey 1981](#)), as being the most likely progenitors of LGRBs due to the mass loss incurred due to stellar wind, allowing for the jets to break out of the stellar envelope. This collapsar model of LGRBs was first supported by observational evidence through the association of half a dozen GRBs with spectroscopically confirmed broad-line Ic supernovae (SNe), as well as photometric evidence of underlying SNe in about two dozen more ([Galama et al. 1998](#); [Stanek et al. 2003](#); [Hjorth et al. 2003, 2011](#); [Woosley & Heger 2006](#)). In addition, there is indirect evidence for the connection of LGRBs with massive stars from the identification of LGRB host galaxies as intensively star-forming galaxies ([Bloom et al. 2002](#); [Le Floc'h et al. 2003](#); [Christensen et al. 2004](#); [Fruchter et al. 2006](#)). The LGRBs are localized in the most active star-forming regions within those

galaxies, increasing the probability that they originate from the death of supermassive stars. Physically, according to the Collapsar model, as the core collapses in a supernova (SN) explosion, a bipolar jet is launched from the center of the star that has to drill through the stellar envelope and break out to produce an observed GRB (e.g., [MacFadyen & Woosley 1999](#); [MacFadyen et al. 2001](#)).

While the evidence for a LGRB-supernovae association ([Bloom et al. 2001](#)) has provided strong support for the collapsar model, the first strong sign of support for the jet-ejecta interaction has come from the off-axis afterglow observations of GRB 170817A (e.g., [Abbott et al. 2017](#); [Goldstein et al. 2017](#); [Savchenko et al. 2017b](#)). In their study, [Bromberg et al. \(2012\)](#) developed a model of LGRBs that provides the first prompt-emission observational imprint of this jet-envelope interaction, and thus, direct confirmation of the collapsar model. A distinct signature in the duration distribution has been detected: the appearance of a plateau toward short durations. This occurs at times much shorter than the typical breakout time of the jet, that is, the time it takes for the jet to drill through the stellar envelope. This action dissipates energy, so the engine driving these jets must be in operation for at least the breakout time. If it is not, a GRB is not produced. The GRB is brief for breakout times that are very close to the engine time and a characteristic plateau is seen in the duration distribution. The breakout time is set by the density and radius of the stellar envelope at radii  $> 10^{10}$  cm. In comparison, the stellar core properties at radii  $< 10^8$  cm determine the engine's working time.

<sup>★</sup> All of the data and code used for our analysis can be found here: <https://github.com/cdslaborg/CollapsarSignature>

<sup>★★</sup> NSF-ASCEND Postdoctoral Fellow.

Unlike LGRBs, SGRBs are theorized to result from the merger of either two neutron stars (NS–NS) or that of a neutron star and a black hole (NS–BH) (Eichler et al. 1989; Narayan et al. 2001; Metzger & Berger 2012; Berger 2014; D’Avanzo 2015). Recently, the first NS–NS merger was confirmed in an unprecedented joint gravitational and electromagnetic observation by Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO), Advanced Virgo, INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL) and the *Fermi* Gamma-ray Space Telescope’s Gamma-ray Burst Monitor (GBM) (Abbott et al. 2017; Goldstein et al. 2017; Savchenko et al. 2017a). Following the discovery of gravitational waves, this was also the first spectroscopically confirmed event associated with a kilonova. Other recent studies using photometry have also found a kilonova event associated with GRB 211211A and GRB 230307A, both consisting of a hard-to-soft prompt emission (Troja et al. 2022; Levan et al. 2024). Compact binary mergers of these types are accompanied by significant dynamical mass ejection. Models differ with respect to how much mass is ejected depending on the GRB, from  $0.03\text{--}0.08 M_{\odot}$  (GRB 130603B) to  $0.1\text{--}0.13 M_{\odot}$  (GRB 060614) (Tanvir et al. 2013; Berger et al. 2013; Yang et al. 2015). The beamed nature of these events has been observed by inspecting breaks in optical and radio bands in GRB 990510 (Harrison et al. 1999). Similar observations of breaks in SGRB afterglows have suggested the involvement of jets as well (Soderberg et al. 2006; Fong et al. 2012). Further supporting evidence for relativistic jets in GRBs has been found thanks to the observation of superluminal motion in GRBs by Taylor et al. (2004), Ghirlanda et al. (2019), Mooley et al. (2018), a phenomenon that is typically seen in the jets of blazars and quasars. Therefore, similarly to the collapsar model, the merger launches a relativistic jet that has to push through the expanding ejecta of significant mass (Murguia-Berthier et al. 2014; Nagakura et al. 2014; Kumar & Zhang 2015; Duffell et al. 2015; Gottlieb et al. 2018). According to Moharana & Piran (2017), this again produces a plateau in the  $T_{90}$  distribution, only at shorter durations than the one seen with LGRBs, reflecting the time it takes for prompt  $\gamma$ -ray emission to become observable after the jet reaches the ejecta’s outer edge.

In this paper, we argue that although the plateaus seen in the analysis of the  $T_{90}$  distributions of GRBs by Bromberg et al. (2012) and Moharana & Piran (2017) could serve as a direct confirmation of theoretical models, they could (with equal plausibility) simply be interpreted as statistical artifacts. This work is organized as follows. Section 2 reviews and dissects the theoretical arguments for the collapsar interpretation of the observed plateau of LGRBs duration distribution. Section 3 details our alternative statistical interpretation of the plateau and our attempt to reproduce the apparent plateaus seen in observational GRB durations from sample incompleteness. Section 4 presents a discussion of our results.

## 2. Collapsar interpretation of the plateau

The argument for the presence of a plateau in the observed duration distribution of LGRBs begins with the assumption that the intrinsic<sup>1</sup> prompt gamma-ray emission duration ( $t_{\gamma}$ ) depends exclusively on the LGRB central engine activity time ( $t_e$ ) and the

jet breakout time ( $t_b$ ) from the stellar envelope,

$$t_{\gamma} = \begin{cases} 0 & \text{if } t_e \leq t_b, \\ t_e - t_b & \text{if } t_e > t_b. \end{cases} \quad (1)$$

Realistically, as Bromberg et al. (2012) stated, the jet breakout, engine working times, and the gamma-ray emission duration might be correlated with each other and other properties of the LGRB progenitor. Nevertheless, assuming the validity of Eq. (1), we can write the probability density function (PDF) of  $t_{\gamma}$  (i.e., the probability distribution of the intrinsic LGRB duration) in terms of the PDF of the engine working time,  $t_e$ ,

$$\pi_{\gamma}(t_{\gamma})dt_{\gamma} = \begin{cases} 0 & \text{if } t_e \leq t_b, \\ \pi_e(t_e)dt_e = \pi_e(t_b + t_{\gamma})dt_{\gamma} & \text{if } t_e > t_b, \end{cases} \quad (2)$$

where  $\pi$  denotes the PDF. In other words, the duration distribution of LGRBs (for a given  $t_b$ ) is simply the tail of the distribution of the engine work time beyond  $t_b$ . Under further assumption that  $\pi_e$  is locally analytic at  $t_e = t_b$ , the Taylor expansion of the right-hand side of Eq. (2) at  $t_e = t_b$  yields,

$$\pi_e(t_b + t_{\gamma}) = \pi_e(t_b) + t_{\gamma} \left. \frac{d\pi_e(t_e)}{dt_e} \right|_{t_e=t_b} + \mathcal{O}(t_{\gamma}^2). \quad (3)$$

Given Eqs. (2) and (3), this implies a nearly constant PDF for the prompt emission duration of LGRBs as  $t_{\gamma} \rightarrow 0$ , that is, if and only if the higher order terms in the Taylor expansion are negligible compared to the first (constant) term. This requires either  $t_{\gamma} \ll t_b$  or for all derivatives of  $\pi_e(t_e)$  near  $t_b$  be nearly zero. Specifically, the second term in the right-hand side of Eq. (3) containing the first derivative of  $\pi_e(t_e)$  must satisfy the following condition:

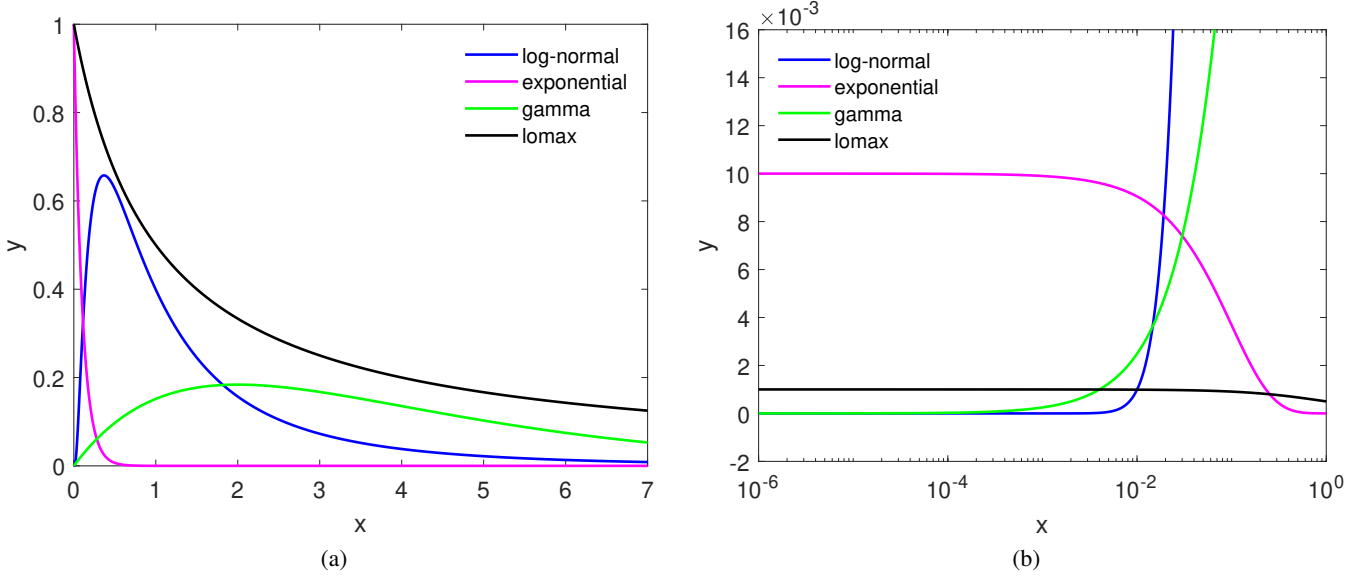
$$\left. \frac{d\pi_e(t_e)}{dt_e} \right|_{t_e=t_b} \ll \frac{\pi_e(t_b)}{t_{\gamma}}. \quad (4)$$

Independent theoretical arguments (e.g., Bromberg et al. 2011) have suggested a typical jet breakout time  $\hat{t}_b \simeq 50$  [s], which is on the same order as the starting point of the plateau behavior in the duration distribution of LGRBs at  $\hat{t}_{\gamma} \simeq 20\text{--}30$  [s] (Bromberg et al. 2012). This similarity ( $\hat{t}_{\gamma} \simeq \hat{t}_b$ ) clearly violates the condition of  $t_{\gamma} \ll t_b$  under which the Taylor expansion is valid. Bromberg et al. (2011, 2012) reconciled this by further assuming  $\pi_e(t_e)$  is a smooth function that “does not vary on short timescales in the vicinity of  $\hat{t}_b$ ,” namely: the first and higher order derivatives in the Taylor expansion must be effectively zero relative to the first constant term in Eq. (3).

Such a strict additional constraint on the derivatives in the Taylor expansion in Eq. (3) leads to a circular logic whereby the collapsar interpretation of the observed nearly-flat plateau in  $t_{\gamma}$  requires the assumption of a nearly-flat plateau in engine working time distribution around  $t_b$ . We recall that  $\pi_{\gamma}(t_{\gamma} > 0) = \pi_e(t_e > t_b)$ , by definition based on Eq. (2). In other words, the collapsar interpretation of the plateau requires the implicit assumption of the existence of the plateau.

The above circular logic can be resolved in several ways: (1) the theoretical predictions of the typical breakout time  $\hat{t} \sim 50$  [s] are imprecise; (2) the distribution of the engine activity time  $\pi_e(t_e)$  is indeed nearly flat around  $\hat{t}_b$ ; or 3) the observed plateau in the duration distribution of LGRBs does not have a collapsar interpretation, but is due, rather, to the statistical nature of the distributions of strictly positive physical quantities combined with sample incompleteness, convolution effects, contamination with SGRBs, and visual effects.

<sup>1</sup> Bromberg et al. (2012) use the keywords “intrinsic” and “observed” interchangeably to represent rest-frame LGRB duration. In this paper, “intrinsic” and “observed” exclusively refer to the GRB rest frame and the observer frame on Earth, respectively.



**Fig. 1.** Illustration of the plateau in the distribution of strictly positive random variables as  $x \rightarrow 0$ . The existence of these plateaus is mathematically guaranteed for all distributions with positive support and finite-valued Probability Density Function (PDF). (a) PDFs of three popular positive-valued statistical distributions. (b) Zoom-in on the same PDFs as in plot (a), but at very small values near the origin, on a logarithmic  $x$ -axis, illustrating the plateau-like behavior of the distributions near  $x = 0$ . The appearance of the plateau near the origin ( $x = 0$ ) is guaranteed by the logarithmic transformation of the  $x$ -axis. The logarithmic transformation effectively spreads a finite amount of variations in the PDF on the  $y$ -axis over a semi-infinite range on the (logarithmic)  $x$ -axis.

In the following section, we argue the last resolution offers a plausible explanation for the apparent plateaus in the duration distributions of both LGRBs and SGRBs, without invoking any physical theories.

### 3. Statistical interpretation of the plateau

Statistical distributions with strictly positive support, for example,  $\pi(t_\gamma), t_\gamma \in (0, +\infty)$ , frequently and naturally exhibit plateaus in their short tails. Such plateaus can appear across a broad range of independent circumstances, as discussed in the following subsections.

#### 3.1. All finite-valued statistical distributions with positive support exhibit plateaus

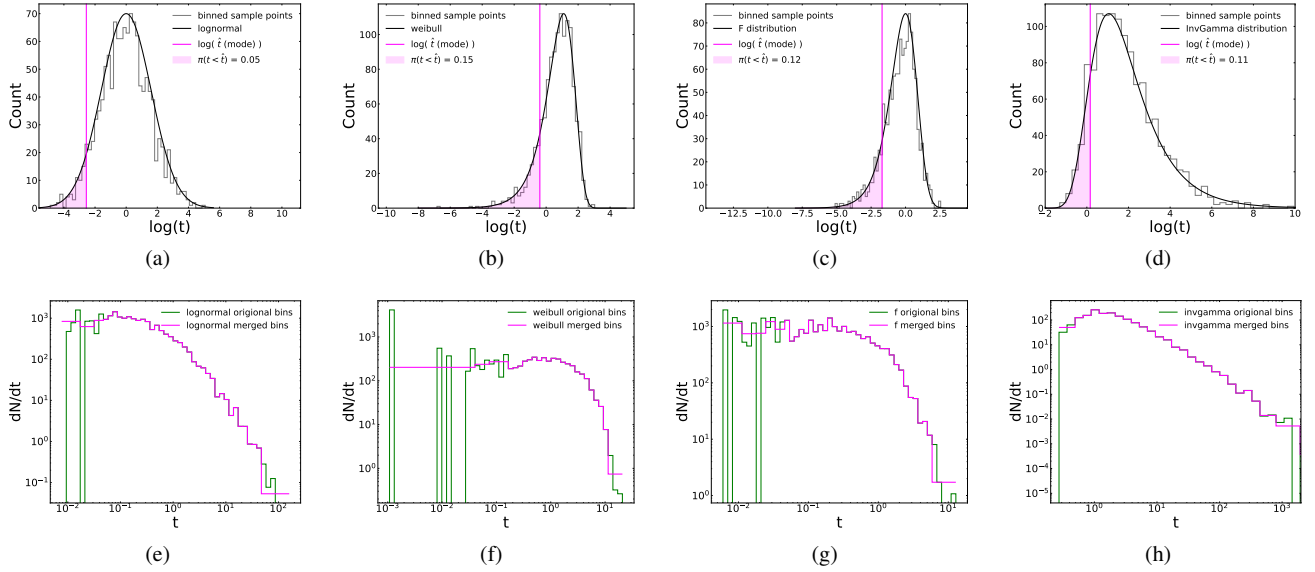
We recall that the Taylor expansion of the PDF of an analytic statistical distribution at any point within its support guarantees the existence of a plateau near the point of expansion. Such a plateau, however, is mathematically infinitesimal, defined only asymptotically as one approaches the point of expansion. Therefore, these mathematically infinitesimal plateaus are invisible to the human eye almost anywhere within the support of the PDF, except at the origin,  $t_\gamma = 0$ , under an appropriate transformation. By definition, the PDF has a positive support  $t_\gamma \in (0, +\infty)$ . Therefore, taking the logarithm of the  $x$ -axis ( $t_\gamma$ ) pushes the lower limit of the support of the PDF at  $t_\gamma = 0$  to negative infinity:  $\log(t_\gamma \rightarrow 0) \rightarrow -\infty$ . This logarithmic transformation of the  $x$ -axis effectively infinitely magnifies the Taylor expansion of  $\pi(t_\gamma)$  around  $t_\gamma = 0$ . This infinite magnification can be intuitively understood by noting that the PDF  $\pi(t_\gamma)$  of the distribution must have a finite value at the origin,  $t_\gamma = 0$ , with a well defined, finite, right-hand derivative. When the  $x$ -axis is logarithmically transformed, the finite amount of changes in  $\pi(t_\gamma)$  span progressively over larger and larger logarithmic ranges on the  $x$ -axis, effectively making the PDF resemble a plateau as  $\log(t_\gamma) \rightarrow -\infty$ .

This is precisely the mechanism by which the collapsar interpretation discussed in Sect. 2 attempts to explain the observed plateau in the duration distribution of LGRBs. However, the collapsar theory of LGRBs invocation appears unnecessary since all finite-valued statistical distributions with strictly positive support exhibit a plateau toward zero, and there is an uncountably infinite number of such statistical distributions. Given that the gamma-ray duration,  $t_\gamma$ , of both SGRBs and LGRBs is a strictly positive-valued observable random variable, the appearance of a plateau in their  $t_\gamma$  distributions on a  $\log(t_\gamma)$ -axis is mathematically guaranteed as  $t_\gamma \rightarrow 0$ . This is true without recourse to any physical theories of GRBs. Figure 1 illustrates this mathematical asymptotic plateau behavior for some well-known continuous distributions with positive real support.

#### 3.2. Sample-incompleteness creates plateaus in observational data

Despite the mathematical guarantee of a plateau in strictly positive finite-valued distributions, the practical visibility of such plateaus in observational data is limited to distributions whose probability mass is heavily concentrated around zero. For an illustration, the near-zero, hard-to-sample, mathematical plateaus of gamma and lognormal distributions from this category are depicted in Fig. 1b.

Sample-incompleteness, however, can still generate a second kind of plateau in strictly positive statistical distributions, entirely different from the plateaus of the first kind of mathematical origin discussed in Sect. 3.1. Such observational plateaus result from limited sampling of positive statistical distributions that are highly positively skewed. We recall that plateaus naturally also occur in the neighborhood of the mode of a distribution where the derivative of the PDF is mathematically zero. This flatness of the PDF around the mode can readily become observationally visible if the distribution sharply rises from some finite value at  $t_\gamma = 0$ , typically  $\pi(t_\gamma = 0) = 0$ , to the PDF mode at



**Fig. 2.** Illustration of the effects of sample incompleteness on plateau formation in statistical distributions. A primary factor in the appearance of finite-sample plateaus near the modes of PDFs is the area to the left of the PDF mode. The smaller this area, the fewer opportunities there are to construct the short tail of the PDFs in finite sampling, thus leading to the appearance of plateaus in the PDFs near their modes. The top plots depict the histograms of the log-transformed random variables drawn from select statistical distributions with positive support. The bottom plots depict the corresponding histograms of the original random variables but on logarithmic axes.

$t_\gamma = \hat{t}$ , and gradually declines to zero as  $t_\gamma \rightarrow +\infty$ . This sharp rise and gradual decay is the typical behavior of many positive-valued statistical distributions and the key requirement for generating finite-sample extended plateaus in their PDFs.

Therefore, if the shape of the distribution (in log–log space) is such that the probability of sampling at  $t_\gamma < \hat{t}$  is negligible, a plateau appears in the histogram of observational data at  $t_\gamma \sim \hat{t}$ . The plateau appearance is substantially strengthened and extended if the PDF decays slowly (and concavely) toward  $+\infty$  and the observational sample is binned and visualized on a logarithmic x-axis as done in Bromberg et al. (2012).

To illustrate this artificial finite-sample plateau creation in action, we considered the lognormal distribution, widely used in astronomy for modeling luminosity functions and other observational data (e.g., Balazs et al. 2003; Butler et al. 2010; Berkhuijsen & Fletcher 2012; Shahmoradi 2013a,b, 2017; Shahmoradi & Nemiroff 2015; Medvedev et al. 2017; Zaninetti 2018; Osborne et al. 2020; Yan et al. 2021). The lognormal distribution is always positively skewed for any parameter values. This results in a typically negligible area to the left of the PDF mode, as illustrated in Figs. 2a and 2e. Hence, the short tail of the lognormal distribution to the left of its mode is rarely fully observationally constructed, leading to the appearance of a plateau in the PDF on the log scale near the distribution mode. This behavior is not exclusive to lognormal and is generically seen in many statistical distributions with positive support, some of which are also shown in the rest of the plots of Fig. 2.

### 3.3. Convolution creates plateaus in observational data

In addition to the area to the left of the mode of PDFs with positive support, the smoothness (differentiability) and concavity of the PDF near its mode play a dominant role in the appearance of finite-sample plateaus. Indeed, a separate class of statistical distributions with strictly positive support has modes that are neither smooth nor occur at the origin. These distributions, as shown by the Pareto and log-Laplace examples, hardly exhibit plateau behavior under finite sampling. Nevertheless, this section shows

that even the most difficult, non-analytic, non-smooth PDFs can exhibit plateaus under convolution.

Recall the convolution of two functions:

$$(f * g)(t) = \int_{-\infty}^{\infty} f(t)g(t - \tau) d\tau, \quad (5)$$

acts as a smoothing operation similar to that of weighted averaging. The resulting function from the convolution will be at least as smooth as the individual functions ( $f(\cdot)$  or  $g(\cdot)$  in Eq. (5)). In fact, the convolution operation is identical to a weighted dynamic averaging of  $f(\cdot)$  when the weight,  $g(\cdot)$ , is a probability density function. In the case of the duration distribution of LGRBs, the convolution performed to obtain the observer-frame duration distribution is as follows:

$$\log(t_{\gamma,\text{obs}}) = \log(z + 1) + \log(t_{\gamma,\text{int}}), \quad (6)$$

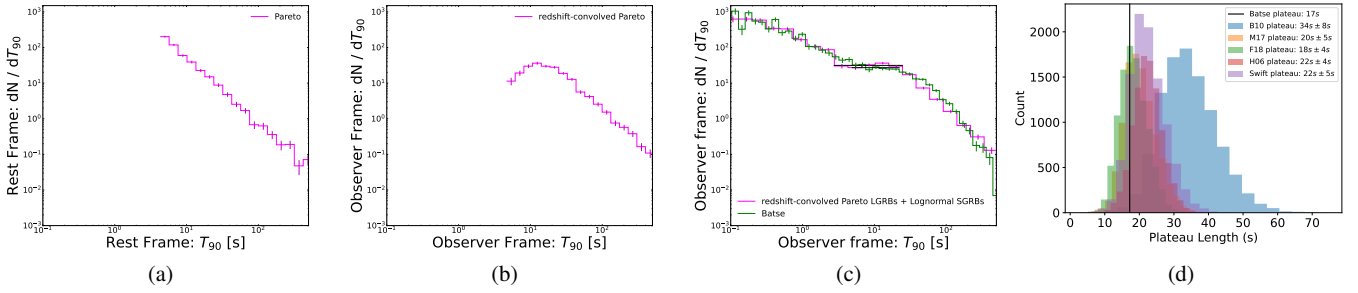
where “obs” and “int” stand for the observed and intrinsic durations, respectively, and  $z$  represents the GRB redshift.

We demonstrate the effectiveness of convolution in creating plateaus by considering a Pareto PDF for the duration distribution of LGRBs. The Pareto distribution does not exhibit any plateau-like behavior within its support under any circumstances (e.g., see Fig. 3a). Yet, when convolved with the redshift distribution of LGRBs detected by the *Neil Gehrels Swift Observatory*<sup>2</sup>, the sharp non-analytical mode of the Pareto PDF transforms into a continuous smooth mode as seen in Fig. 3b. Combining the observed convolved duration distribution of LGRBs with the duration distribution of SGRBs further eliminates the appearance of any discontinuity or sharp decline in the short tail of the distribution, leading to a plateau in the mixture distribution that is even longer than the observed plateaus in the duration distributions of The Burst And Transient Source Experiment (BATSE) and *Fermi* catalog GRBs (Fig. 3c).

To verify the generality of convolution effects on plateau creation, we also considered four additional popular GRB formation rate scenarios, each in 10 000 independent simulations:

<sup>2</sup> All redshifts are taken from the *Swift* GRB catalog.





**Fig. 3.** Illustration of the smoothing effects of convolution on the Pareto distribution, leading to the appearance of a plateau in the  $\frac{dN}{dT}$  plot. (a) Sampled points from a Pareto distribution after performing the bin merging as described in Bromberg et al. (2012). (b) Same data as in plot (a) but convolved with the redshift distribution of LGRBs (derived from *Swift* catalog). (c) Convolved observed duration distribution of LGRBs combined with a lognormal fit to the redshift distribution of SGRBs. For comparison, the green line represents the duration distribution of the BATSE SGRBs and LGRBs. The final observed plateau resulting from the Pareto distribution is 50% longer than the observed plateau in the duration distribution of BATSE LGRBs. (d) Distribution of the average plateau lengths, assuming an intrinsic Pareto duration distribution convolved with various GRB popular redshift distribution scenarios from the literature as listed in the plot legend. The observed plateau length in the BATSE duration data is illustrated by the vertical black line.

Fermi-LAT Collaboration (2018) (F18), Madau & Fragos (2017) (M17), Butler et al. (2010) (B10), and Hopkins & Beacom (2006) (H06). The data modeling and fittings were performed by assuming one of these redshift models as the redshift distribution of LGRBs and assuming a parametric form for the intrinsic duration distribution of LGRBs (e.g., Pareto), using a Bayesian fitting approach, as described in Shahmoradi (2013b, 2017), Shahmoradi & Nemiroff (2015), Osborne et al. (2020) assuming non-informative objective priors for all unknown parameters. Once the model fitting was carried out, random redshift samples of the same size as the observational duration distribution data were generated by sampling the corresponding redshift distribution models with an adaptive Markov chain Monte Carlo algorithm (Shahmoradi & Bagheri 2020, 2021; Shahmoradi et al. 2020; Kumbhare & Shahmoradi 2020). The random samples were subsequently convolved with the random samples from the corresponding duration distribution models with the best-fit parameters to generate the observed duration distributions. This procedure was repeated 10 000 times for each modeling and redshift distribution scenario. Finally, the lengths of the resulting apparent plateaus in the duration distributions for each of the 10 000 simulations per modeling scenario were measured using the same approach as in Bromberg et al. (2012).

The histograms of the resulting plateau lengths for each of the five redshift distribution scenarios are illustrated in plot d of Fig. 3d. Notably, the resulting average plateau lengths from the convolution of a Pareto duration distribution with all GRB formation rate scenarios are longer than the plateau length in BATSE observational data.

### 3.4. Sample contamination creates plateaus in observational data

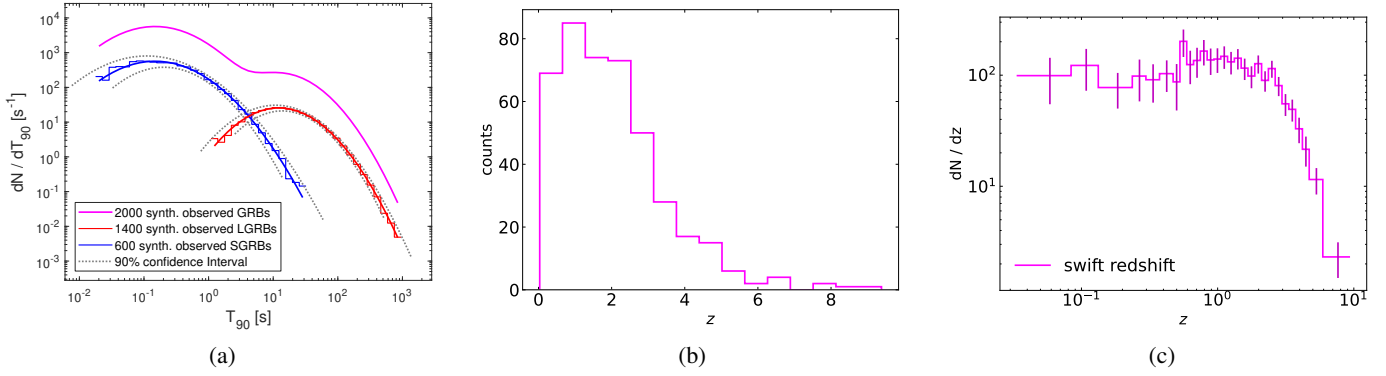
A contamination of the short tail of the duration distribution of LGRBs with SGRBs leads to a further extension of the apparent plateaus because the population of SGRBs compensates for any drop in the count of LGRBs toward low durations. Again, we considered a lognormal fit for the intrinsic duration distribution of LGRBs. Shahmoradi (2013a,b), Shahmoradi & Nemiroff (2015), Osborne et al. (2020) argued and provided evidence for the goodness of fit of LGRBs and SGRBs prompt duration distributions with lognormal PDF. The lognormal distribution does not exhibit an inherent plateau near its short tail. Sample incompleteness, however, creates the appearance of a plateau in the

lognormal fit to the observational LGRB data. This apparent plateau is further extended by the convolution of the intrinsic duration distribution with redshift to obtain the observe-frame duration distribution as illustrated in Fig. 4a. Finally, the contamination with SGRB data due to the overlap of the two distributions completely eradicates any signs of decline in the short tail of LGRBs duration distribution, yielding a perfect plateau appearance in the final mixture distribution, as shown by the magenta solid curve in Fig. 4a.

## 4. Discussion

In this paper, we present statistical arguments that strongly favor a non-physical (i.e., non-collapsar) origin for the observed plateau in the duration distribution of LGRBs. The Taylor expansion in Eq. (3) of the density function of the engine activity time ( $t_e$ ) near the jet breakout time ( $t_b$ ) requires the plateau to appear at durations orders of magnitude smaller than the inferred  $t_b$  in Bromberg et al. (2012). Bromberg et al. (2011, 2012) reconciled this inconsistency by an additional assumption of the engine activity time as “a smooth function” that not vary on short timescales near the breakout time. However, this leads to a circular logic in the argument for the collapsar origin of the observed plateau, where Bromberg et al. (2012) imposed a flatness condition on the distribution of the engine activity time near the breakout time to obtain a flatness in the prompt duration of LGRBs; by definition as per Eq. (2), this is the same as the engine activity time at  $t_\gamma > t_b$ . Alternatively, we can interpret the plateau in the duration distribution of LGRBs as a constraint on the shape of the engine activity time, under the assumption that the prompt gamma-emission duration precisely reflects the engine activity time at  $t_\gamma > t_b$ , as proposed in Bromberg et al. (2011, 2012). In either case, the plateau in the duration distribution of LGRBs does not appear to serve as an observational imprint of the collapsar model.

We further question any physical origins of the observed plateau by showing that plateaus are ubiquitous in the short tails of statistical distributions with strictly positive support (e.g., Fig. 2) and frequently result from a combination of sample incompleteness with the extremely positively skewed nature of such distributions (on natural axes). Even where the intrinsic duration distribution of LGRBs does not exhibit a plateau behavior in its short tail, we show that its convolution with a redshift distribution can create observed duration distributions that exhibit plateau-like behavior. The presence and extent of the plateaus are further significantly

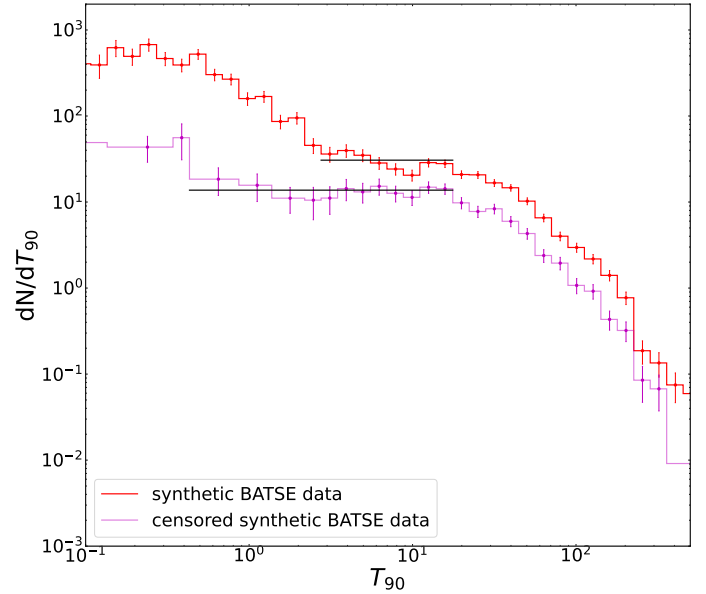


**Fig. 4.** BATSE-detectable samples of 600 SGRBs and 1400 LGRBs are randomly generated from our respective Monte Carlo Universes. (a) SGRBs, represented by the blue bins and LGRBs by the red bins, where each bin is the 50th percentile value of 10 000 synthetic detections. The solid blue and red lines are lognormal fits to the bins in the pre-transformed space. These two fits are summed to produce the solid magenta line multiplied by a factor of 10 to offset it for clarity. The dotted gray lines represent the 90% confidence interval for each binned distribution. (b) Distribution of observed *Swift* redshifts in linear space. (c) Redshift distribution transformed in the same manner as the duration distribution throughout this manuscript. After performing the transformation described in Bromberg et al. (2012), the resulting plot displays a plateau in the log–log space, although there is no apparent physical origin.

enhanced if SGRBs mix with and contaminate the observed duration distribution of LGRBs, as is the case with all major GRB catalogs. An example of a perfect plateau resulting from such contamination is depicted in Fig. 4a.

To resolve the sample contamination problem and minimize the impact of SGRBs duration distribution on the observed plateau in the duration distribution of LGRBs, Bromberg et al. (2012) also restricted their analysis only to soft LGRBs in the BATSE catalog. This is done by removing any events with a hardness ratio<sup>3</sup> above 2.6. This artificial cutoff preferentially excludes SGRBs from the duration histogram and significantly extends the observed plateau of LGRBs to more than twice the original length. However, in contrast to the arguments of Bromberg et al. (2012), this plateau extension in the population of soft LGRBs has no connection with the collapsar interpretation of the plateau. It is merely an artifact of further censorships and sample incompleteness caused by the exclusion of an arbitrarily chosen subset of data. To illustrate this phenomenon, we followed Shahmoradi (2013b), Shahmoradi & Nemiroff (2015), Osborne et al. (2020) to fit the BATSE catalog data with a comprehensive model for the duration, spectral peak energy, peak luminosity, and isotropic energy of GRBs. Notably, we assumed that the duration distributions of both LGRBs and SGRBs follow lognormal, making no assumption on the existence of plateaus in the duration distributions. Once the fitting was performed, we followed the prescription of Bromberg et al. (2012) to remove the observed events from our Monte Carlo Universe with hardness ratios larger than 2.6. Figure 5 compares the resulting duration histogram for the soft population of LGRBs with the original histogram from the Monte Carlo Universe. A few remarks are in order, as follows.

Firstly, plateaus appear in the duration distributions of both LGRBs and SGRBs without even requiring their existence in the model. Secondly, the LGRB plateau extends to about two orders of magnitude when we follow the prescription of Bromberg et al. (2012) to exclude short hard bursts from the histogram. While it is indeed purely statistical, this plateau extension is on par with the reported extension Bromberg et al. (2012) found in the BATSE catalog data.



**Fig. 5.** Illustration of the impact of excluding SGRBs from the duration distribution on the observed plateau of LGRBs. The original plateau in the red histogram and the extension of it by removing SGRBs in the magenta histogram are purely statistical (resulting from the lognormal fits to data as depicted in Fig. 4a) and have no connections to the physics of GRBs or collapsars whatsoever.

The specific binning approach used to construct histograms of data also appears to moderately (and even significantly) impact the strength and extent of any plateau in the short tails of distributions. This binning effect is well illustrated in Figs. 2e,f, and g. The above arguments point to a non-physical origin for the observed plateau in the duration distribution of LGRBs. In fact, the distributions of other observational properties of GRBs (e.g., the observed redshift distribution as seen in Fig. 4c) also exhibit plateaus without any apparent physical origins.

The plateau emerging within the LGRB duration distribution is not unique and can also be seen in the population of SGRBs. Unlike the population of LGRBs, the decline in the short tail of the duration distribution of SGRBs is readily seen. This decline in the short tail actually suggests the reason why we do not see

<sup>3</sup> The hardness ratio is defined as the ratio of fluence between BATSE energy channels. In this case, channels 3 (100–300 keV) and 2 (50–100 keV)

such a fall in the short tails of LGRBs duration distribution. Unlike the case of LGRBs, no additional mixing distribution “covers” this decline in the SGRB population. Such a plateau in the SGRB duration distribution is hard to reconcile with the non-collapsar origin of SGRBs. Moharana & Piran (2017) proposed a similar prompt emission mechanism to that of LGRBs (by requiring the SGRB jet to drill through an envelope) to explain the non-collapsar plateau seen in the duration distribution of SGRBs. The likelihood ratio test used in Moharana & Piran (2017) for comparing the performances of the lognormal and plateau models to observational data only applies to nested statistical models, while the models compared are non-nested with entirely different parameters. To compare the goodness of fit of different models to the combined SGRB and LGRB BATSE data, we also considered four modeling scenarios: the lognormal+lognormal mixture model as illustrated in Fig. 4; the proposed plateau+powerlaw-plateau+powerlaw(tapered) mixture model as in Eq. (3) in Moharana & Piran (2017); lognormal-plateau+powerlaw(tapered) mixture model; and plateau+powerlaw-lognormal mixture model. The resulting fits yield the corresponding Bayesian information criterion (BIC) scores of: 8339, 8354, 8360, and 8362, implying that the observational SGRB/LGRB data is  $\sim 3 \times 10^6$ – $10^9$  times more likely to have originated from a lognormal+lognormal mixture model than any alternative models with plateaus for the duration distributions of either or both GRB classes.

By contrast, the statistical arguments presented in this manuscript offer a natural explanation for plateaus in the duration distributions of both GRB populations without recourse to any physical arguments and origins of GRBs. The fact that a wide variety of statistical distributions fit the duration distributions of GRBs equally well, as we demonstrate in this work, further corroborates the findings of Ghirlanda et al. (2015), Salafia et al. (2020) and serves as a reminder to exercise caution in attributing the observed plateaus in the duration distributions of GRBs to their physics.

In summary, we present an alternative equally plausible purely statistical origin for the observed plateaus in the duration distributions of LGRBs and SGRBs. Our analysis further signifies the relevance and importance of selection effects and data censorship (e.g., Petrosian & Lee 1996; Lloyd & Petrosian 1999; Petrosian et al. 1999, 2015; Lloyd et al. 2000; Hakkila et al. 2003; Band & Preece 2005; Nakar & Piran 2004; Shahmoradi & Nemiroff 2009, 2011a,b; Butler et al. 2007, 2009, 2010; Shahmoradi 2013a; Coward et al. 2015; Osborne et al. 2020, 2021; Bryant et al. 2021; Tarnopolski 2021) in data-driven studies of the Physics of GRBs.

**Acknowledgements.** F.B. acknowledges NSF-ASCEND Postdoctoral Fellowship support by the US National Science Foundation. All authors contributed equally to this manuscript. We appreciate the anonymous referee’s careful and constructive comments, which significantly improved the quality of this manuscript’s scientific contents.

## References

Abbott, B. P., Abbott, R., Abbott, T., et al. 2017, *Phys. Rev. Lett.*, **119**, 161101  
 Balazs, L. G., Bagoly, Z., Horváth, I., Mészáros, A., & Mészáros, P. 2003, *A&A*, **401**, 129  
 Band, D. L., & Preece, R. D. 2005, *ApJ*, **627**, 319  
 Berger, E. 2014, *ARA&A*, **52**, 43  
 Berger, E., Fong, W., & Chornock, R. 2013, *ApJ*, **774**, L23  
 Berkhuijsen, E. M., & Fletcher, A. 2012, *Eur. Astron. Soc. Publ. Ser.*, **56**, 243  
 Bloom, J. S., Frail, D. A., & Sari, R. 2001, *AJ*, **121**, 2879  
 Bloom, J. S., Kulkarni, S. R., Price, P., et al. 2002, *ApJ*, **572**, L45  
 Bromberg, O., Nakar, E., & Piran, T. 2011, *ApJ*, **739**, L55

Bromberg, O., Nakar, E., Piran, T., et al. 2012, *ApJ*, **749**, 110  
 Bryant, C. M., Osborne, J. A., & Shahmoradi, A. 2021, *MNRAS*, **504**, 4192  
 Butler, N. R., Kocevski, D., Bloom, J. S., & Curtis, J. L. 2007, *ApJ*, **671**, 656  
 Butler, N. R., Kocevski, D., & Bloom, J. S. 2009, *ApJ*, **694**, 76  
 Butler, N. R., Bloom, J. S., & Poznanski, D. 2010, *ApJ*, **711**, 495  
 Christensen, L., Hjorth, J., & Gorosabel, J. 2004, *A&A*, **425**, 913  
 Coward, D., Howell, E., Wan, L., & Macpherson, D. 2015, *MNRAS*, **449**, L6  
 D’Avanzo, P. 2015, *J. High Energy Astrophys.*, **7**, 73  
 Duffell, P. C., Quataert, E., & MacFadyen, A. I. 2015, *ApJ*, **813**, 64  
 Eichler, D., Livio, M., Piran, T., & Schramm, D. N. 1989, *Nature*, **340**, 126  
 Fong, W.-F., Berger, E., Margutti, R., et al. 2012, *ApJ*, **756**, 189  
 Fermi-LAT Collaboration 2018, *Science*, **362**, 1031  
 Fruchter, A., Levan, A., Strolger, L., et al. 2006, *Nature*, **441**, 463  
 Galama, T. J., Vreeswijk, P., Van Paradijs, J., et al. 1998, *Nature*, **395**, 670  
 Ghirlanda, G., Bernardini, M. G., Calderone, G., & D’Avanzo, P. 2015, *J. High Energy Astrophys.*, **7**, 81  
 Ghirlanda, G., Salafia, O. S., Paragi, Z., et al. 2019, *Science*, **363**, 968  
 Goldstein, A., Veres, P., Burns, E., et al. 2017, *ApJ*, **848**, L14  
 Gottlieb, O., Nakar, E., & Piran, T. 2018, *MNRAS*, **473**, 576  
 Hakkila, J., Giblin, T. W., Roiger, R. J., et al. 2003, *ApJ*, **582**, 320  
 Harrison, F., Bloom, J., Frail, D. A., et al. 1999, *ApJ*, **523**, L121  
 Hjorth, J., Sollerman, J., Møller, P., et al. 2003, *Nature*, **423**, 847  
 Hjorth, J., Bloom, J., Kouveliotou, C., Wijers, R., & Woosley, S. 2011, in *Cambridge Astrophysics Series*, eds. C. Kouveliotou, R. Wijers, & S. Woosley (Cambridge: Cambridge Univ. Press), 51  
 Hopkins, A. M., & Beacom, J. F. 2006, *ApJ*, **651**, 142  
 Kouveliotou, C., Meegan, C. A., Fishman, G. J., et al. 1993, *ApJ*, **413**, L101  
 Kumar, P., & Zhang, B. 2015, *Phys. Rep.*, **561**, 1  
 Kumbhare, S., & Shahmoradi, A. 2020, ArXiv e-prints [arXiv:2010.04190]  
 Le Floc’h, E., Duc, P.-A., Mirabel, I., et al. 2003, *A&A*, **400**, 499  
 Levan, A. J., Gompertz, B. P., Salafia, O. S., et al. 2024, *Nature*, **626**, 737  
 Lloyd, N. M., & Petrosian, V. 1999, *ApJ*, **511**, 550  
 Lloyd, N. M., Petrosian, V., & Mallozzi, R. S. 2000, *ApJ*, **534**, 227  
 MacFadyen, A., & Woosley, S. 1999, *ApJ*, **524**, 262  
 MacFadyen, A. I., Woosley, S., & Heger, A. 2001, *ApJ*, **550**, 410  
 Madau, P., & Fragos, T. 2017, *ApJ*, **840**, 39  
 Massey, P. 1981, *ApJ*, **246**, 153  
 Medvedev, A., Kholtygin, A., Hubrig, S., et al. 2017, *Astron. Nachr.*, **338**, 910  
 Metzger, B. D., & Berger, E. 2012, *ApJ*, **746**, 48  
 Moharana, R., & Piran, T. 2017, *MNRAS*, **472**, L55  
 Mooley, K., Deller, A., Gottlieb, O., et al. 2018, *Nature*, **561**, 355  
 Murguía-Berthier, A., Montes, G., Ramirez-Ruiz, E., De Colle, F., & Lee, W. H. 2014, *ApJ*, **788**, L8  
 Nagakura, H., Hotokezaka, K., Sekiguchi, Y., Shibata, M., & Ioka, K. 2014, *ApJ*, **784**, L28  
 Nakar, E., & Piran, T. 2004, *MNRAS*, **360**, 73  
 Narayan, R., Piran, T., & Kumar, P. 2001, *ApJ*, **557**, 949  
 Osborne, J. A., Shahmoradi, A., & Nemiroff, R. J. 2020, *ApJ*, **903**, 33  
 Osborne, J. A., Bagheri, F., & Shahmoradi, A. 2021, *MNRAS*, **502**, 5622  
 Petrosian, V., & Lee, T. T. 1996, *ApJ*, **467**, L29  
 Petrosian, V., Lloyd, N., & Lee, A. 1999, *ASP Conf. Ser.*, **190**, 235  
 Petrosian, V., Kitanidis, E., & Kocevski, D. 2015, *ApJ*, **806**, 44  
 Poolakkil, S., Preece, R., Fletcher, C., et al. 2021, *ApJ*, **913**, 60  
 Salafia, O., Barbieri, C., Ascenzi, S., & Toffano, M. 2020, *A&A*, **636**, A105  
 Savchenko, V., Ferrigno, C., Kuulkers, E., et al. 2017a, *PoS, IFS2017*, 058  
 Savchenko, V., Ferrigno, C., Kuulkers, E., et al. 2017b, *ApJ*, **848**, L15  
 Shahmoradi, A. 2013a, ArXiv e-prints [arXiv:1308.1097]  
 Shahmoradi, A. 2013b, *ApJ*, **766**, 111  
 Shahmoradi, A. 2017, ArXiv e-prints [arXiv:1711.10599]  
 Shahmoradi, A., & Bagheri, F. 2020, ArXiv e-prints [arXiv:2008.09589]  
 Shahmoradi, A., & Bagheri, F. 2021, *J. Open Source Softw.*, **6**, 2741  
 Shahmoradi, A., & Nemiroff, R. 2009, *AIP*, **1133**, 425  
 Shahmoradi, A., & Nemiroff, R. 2011a, *Bull. Am. Astron. Soc.*, **43**  
 Shahmoradi, A., & Nemiroff, R. J. 2011b, *MNRAS*, **411**, 1843  
 Shahmoradi, A., & Nemiroff, R. J. 2015, *MNRAS*, **451**, 126  
 Shahmoradi, A., Bagheri, F., & Osborne, J. A. E. 2020, ArXiv e-prints [arXiv:2010.00724]  
 Soderberg, A. M., Kulkarni, S. R., Nakar, E., et al. 2006, *Nature*, **442**, 1014  
 Stanek, K. Z., Matheson, T., Garnavich, P., et al. 2003, *ApJ*, **591**, L17  
 Tanvir, N., Levan, A., Fruchter, A., et al. 2013, *Nature*, **500**, 547  
 Tarnopolski, M. 2021, *MNRAS*, **507**, 1450  
 Taylor, G., Frail, D., Berger, E., & Kulkarni, S. 2004, *ApJ*, **609**, L1  
 Troja, E., Fryer, C., O’Connor, B., et al. 2022, *Nature*, **612**, 228  
 Woosley, S., & Bloom, J. 2006, *ARA&A*, **44**, 507  
 Woosley, S., & Heger, A. 2006, *ApJ*, **637**, 914  
 Yan, Y., He, H., Li, C., et al. 2021, *MNRAS*, **505**, L79  
 Yang, B., Jin, Z.-P., Li, X., et al. 2015, *Nat. Commun.*, **6**, 1  
 Zaninetti, L. 2018, *Adv. Astrophys.*, **3**, 239