New insights on the duration distribution of long GRBs from Collapsars

O. Bromberg[*a], **E. Nakar**[ab], **T. Piran**[a] **& R. Sari**[a]

[a]*Racah Institute of Physics, The Hebrew University, 91904 Jerusalem, Israel*
[ab]*The Raymond and Berverly Sackler School of Physics and Astronomy, Tel Aviv University, 69978 Tel Aviv, Israel*
E-mail: omerb@phys.huji.ac.il

According the Collapsar model long gamma-ray bursts (LGRBs) involve relativistic jets that puncture the envelope of a collapsing star, and produced the γ-rays after they break out. This model provides a theoretical framework for the well known association between LGRBs and massive stars. However although this association is supported by a wealth of observations, to this date there is no direct observational evidence for the emergence of the jet from the star. In other words there is no direct evidence for the Collapsar model. Here we show that a distinct signature of the Collapsar model is the appearance of a plateau in the duration distribution of the prompt GRB emission at times much shorter than the typical breakout time of the jet. This plateau is evident in the data of all major GRB satellites, and provides a direct evidence supporting the Collapsar model. It also enables us to place limits on the sizes and masses of LGRB progenitors; suggests the existence of a large population of choked (failed) GRBs; and indicates that the 2 s duration commonly used to separate Collapsars and non-Collapsars holds for BATSE and possibly Fermi GBM GRBs, but it is inconsistent with the duration distributions of *Swift* GRBs.

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[*]Speaker.

1. Introduction

The connection of long GRBs (LGRBs) to collapsing massive stars is strongly supported by a wealth of observational evidence. The most notable evidence is the association of half a dozens GRBs with spectroscopically confirmed broad-line Ic supernovae (SNe), and the identification of "red bumps" in the afterglows of about two dozens more, which shows a photometric evidence of underlying SNe. The model that provides the theoretical framework of this association is known as the Collapsar model (MacFadyen & Woosley, 1999; MacFadyen et al., 2001). According to this model, following the core collapse of a massive star, a bipolar jet is launched at the center of the star. The jet drills through the stellar envelope and breaks out of the surface before producing the observed γ-rays. However, although this model is supported indirectly by the LGRB-SN association, to this date we could not identify a clear direct observational imprint of the jet-envelope interaction, thus there is no direct confirmation yet of the Collapsar model.

Here we show that under very general conditions the time that the jet spends drilling through the star leads to a plateau in the duration distribution of the GRBs at times much shorter than the breakout time of the jet. This plateau exists in the duration distribution of all major GRB satellites, and provides a strong observational support for the Collapsar model. An analysis of this plateau also (i) supports the hypothesis of compact stellar progenitors, (ii) implies the existence of a large population of chocked jets that fail to break out of their progenitor stars and (iii) enables us to determine statistically the fraction of non-Collapsars from the total GRB sample and the threshold duration that separates Collapsars from non-Collapsars. Specifically it shows that this time differs from one satellite to the other.

2. The propagation of a jet in the stellar envelope

The jet propagates in the star by pushing the stellar material in front of it, leading to the formation of a "head" of shocked matter at its front. The head propagates at sub relativistic velocities along most of the star (Matzner, 2003; Zhang et al., 2003; Morsony et al., 2007; Mizuta & Aloy, 2009; Bromberg et al., 2011a), even though the jet is ejected at relativistic velocities. Therefore as long as the head is inside the star it dissipates most of the jet energy, and it needs to be constantly supported by the relativistic jet material to propagate. This implies that there is a minimal amount of time, t_b, that the jet engine needs to operate to get a successful jet breakout (Bromberg et al., 2011b):

$$t_b \simeq 15 \text{ s} \cdot \left(\frac{L_{iso}}{10^{51} \text{ erg/s}} \right)^{-1/3} \left(\frac{\theta}{10°} \right)^{2/3} \left(\frac{R_*}{5R_\odot} \right)^{2/3} \left(\frac{M_*}{15M_\odot} \right)^{1/3}, \qquad (2.1)$$

where L_{iso} is the isotropic equivalent jet luminosity, θ is the jet half opening angle and we have used typical values for a long GRB. R_* and M_* are the radius and the mass of the progenitor star, where we normalize their value according to the typical radius and mass inferred from observations of the few supernovae (SNe) associated with long GRBs. If the activity time of the engine $t_e < t_b$ the jet fails to escape and a regular long GRB is not observed.

After the jet breaks out of the star it expands and produces the observed γ-ray emission at large distances from the stellar surface. In most GRB models (e.g. Sari & Piran, 1997) the observed

duration of the GRB, t_γ, reflects the activity time of the central engine after the break out of the jet

$$t_\gamma = t_e - t_b. \tag{2.2}$$

The distribution of t_γ is therefore a convolution of the distributions of the engine activity time and the breakout time combined with cosmological redshift effects.

3. The duration distribution of Collapsars

Under very general conditions, Eq. 2.2 results in a flat distribution of t_γ at durations significantly shorter than the typical breakout time. A simple way to show that is by considering a single value of t_b for all Collapsars and ignoring, for simplicity, cosmological redshifts and detector threshold effects. The probability that a GRB has a duration t_γ equals, in this case, to the probability that the engine operating time is $t_\gamma + t_b$, i.e.

$$p_\gamma(t_\gamma)dt_\gamma = p_e(t_b + t_\gamma)dt_\gamma, \tag{3.1}$$

where p_γ is the probability distribution of the observed durations and p_e is the probability distribution of the engine operating times. It is clear that $p_e(t_b + t_\gamma) \approx p_e(t_b) = $ const for any $t_\gamma \ll t_b$. Moreover, if $p_e(t_e)$ is a smooth function that does not vary rapidly in the vicinity of $t_e \approx t_b$, over a duration of the scale of t_b, then the constant distribution is extended up to times $t_\gamma \lesssim t_b$. In the case of interest t_b and t_e are determined by different regions of the star: the breakout time is set by the density and radius of the stellar envelope at radii $> 10^{10}$ cm, while t_e is determined by the stellar core properties at radii $< 10^8$ cm. The core and the envelope are weakly coupled (Crowther, 2007) and the engine is unaware whether the jet has broken out or not. Therefore, it is reasonable to expect that $p_e(t_e)$ is smooth in the vicinity of $t_e \approx t_b$ and $p_\gamma(t_\gamma) \approx$ const for $t_\gamma \lesssim t_b$. In the opposite limit, where $t_b \ll t_\gamma$, then $t_\gamma \approx t_e$. Together eq. 3.1 reads:

$$p_\gamma(t_\gamma) \approx \begin{cases} p_e(t_b) & t_\gamma \lesssim t_b \\ p_e(t_\gamma) & t_\gamma \gg t_b \end{cases}, \tag{3.2}$$

Remarkably, as we show in Bromberg et al. (2011c), the plateau exists also in the more general case, when t_b varies and the redshift distribution and detector thresholds are considered. The constant value of t_b, in this case, should be replaced by a "typical" breakout time, $\hat{t}_b$, modulo redshift corrections. This plateau in the GRB duration distribution is independent of specific details of the relevant distributions and in particular of the details of p_e. It is a direct prediction of the Collapsar model that follows immediately from Eq. 2.2. Given an average redshift $\overline{(1+z)} \sim 3$ and Eq. 2.1, we expect the effective (redshift corrected) typical breakout time to be of order 50 s. At long observed durations, $t_\gamma \gg \hat{t}_b$, the distribution p_γ is determined by a convolution of p_e and the distributions of the breakout times and bursts' redshifts. However p_γ cannot be flatter than p_e, otherwise p_e would dominate the distribution. Therefore, an extrapolation of $p_\gamma(t_\gamma \gg \hat{t}_b)$ to durations shorter than $\hat{t}_b$ provides a lower limit to the number of events with $t_e < \hat{t}_b$. Namely, it is an estimate of the minimal number of choked bursts. At very short durations (less than 2 s) an additional population of shorter and harder GRBs (SGRBs) appears (Kouveliotou et al., 1993). It is well established that most SGRBs are not associated with death of massive stars (Nakar, 2007,
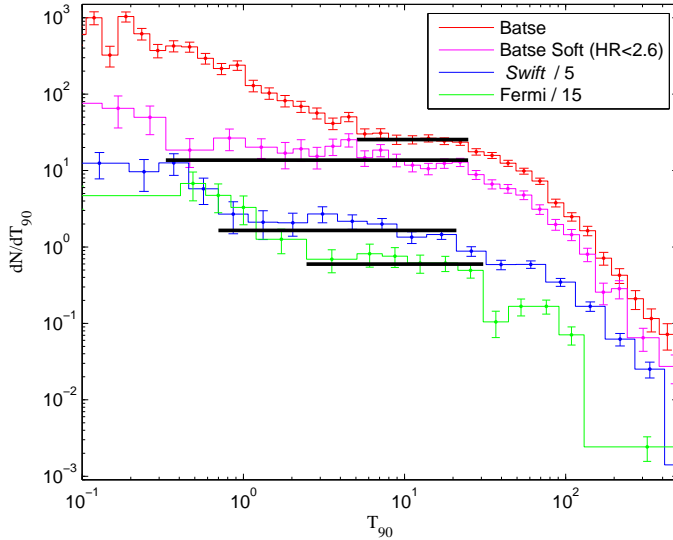
Figure 1: The T_{90} distribution, dN/dT_{90}, of BATSE (red), *Swift* (blue) and Fermi GBM (green) GRBs. Also plotted is the distribution of the soft ($HR < 2.6$) BATSE bursts (magenta). For clarity the *Swift* values are divided by a factor of 5 and the Fermi GBM by 15. At shorter times the sample is dominated by non-Collapsars. Note that the quantity dN/dT is depicted and not $dN/d\log T$ as traditionally shown in such plots (e.g., Kouveliotou et al., 1993). The black lines show the best fitted flat interval in each data set: $5-25$ s (BATSE), $0.7-21$ s (*Swift*), and $2.5-31$ s (Fermi). The upper limits of this range indicate a typical breakout time of a few dozens seconds, in agreement with the prediction of the Collapsar model. The distribution at times $\gtrsim 100$ s can be fitted by a power law with an index $-4 < \alpha < -3$. The soft BATSE bursts show a considerably longer plateau ($0.4-25$ s), indicating that most of the soft short bursts are in fact Collapsars (Bromberg et al., 2011c).

and references there in), namely they are non-Collapsars, and the above argument of a flat distribution doesn't apply to them. Therefore, when considering the overall burst duration distribution we expect a flat section for durations significantly shorter than 50 s down to the duration where these non-Collapsars dominate.

4. The observed distribution of the prompt GRB durations

The observed duration of a GRB is characterized by $T_{90} \approx t_\gamma(1+z)$, during which 90% of the fluence is accumulated. Fig. 1 depicts the observed distribution of T_{90} for the three major GRB satellites: BATSE[1], *Swift*[2] and Fermi GBM [3]. Note that we plot the quantity $p_\gamma(T_{90}) = dN/dT$ and not $dN/d\log T$ traditionally shown in such plots (Kouveliotou et al., 1993). As predicted, a plateau around 2-30 s is clearly seen in all distributions. The extent of the plateau varies slightly from one detector to another. This is expected given the different detection threshold sensitivities in different energy windows (see below). The regions marked in solid bold lines in Fig. 1 are consistent with a flat distribution with a χ^2 per degree of freedom of $0.6, 1.3, 0.7$ for BATSE, *Swift* and Fermi respectively (see Bromberg et al., 2011c, for details). At the high end of the plateau the

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[1]http://swift.gsfc.nasa.gov/docs/swift/archive/grb_table

[2]http://gammaray.msfc.nasa.gov/batse/grb/catalog/current/

[3]http://lyra.berkeley.edu/grbox/grbox.php

T_{90} distribution decreases rapidly and can be fitted at long durations (>100 s) by a power law with an index, α, in the range $-4 < \alpha < -3$.

To test our hypothesis that the plateau in the duration distribution indeed reflects the distribution of Collapsars and is not, for example, a consequence of adding two separate distributions: one decreasing (SGRBs) and one increasing (LGRBs), we also plot the distribution, dN/dT, of soft BATSE bursts (magenta). Since non-Collapsars are harder on average (Kouveliotou et al., 1993), we expect this sample to be less contaminated and the plateau to extend to shorter durations than in the whole BATSE sample. Considering the soft bursts as bursts with hardness ratio[4], $HR < 2.6$, the median value of bursts with $T_{90} > 5$ s, we find that the plateau in this sample extends from 25 s down to 0.4 s (1.3 χ^2/dof), an order of magnitude lower than the original 5 s in the complete sample. This lands a strong support to the conclusion that the observed flat distribution is indeed indicating on the Collapsar origin of the population. It also implies that HR is a good indicator that effectively filters out a large number of non-Collapsars from the BATSE GRB sample.

5. The fraction of non-Collapsar SGRBs

At short durations, the GRB distribution is dominated by the non-Collapsars SGRBs (Nakar, 2007, and references there in). These bursts are hard to classify since all their hard energy properties largely overlap with those of the Collapsars (Nakar, 2007). The least overlap is in the duration distributions and hence, traditionally a burst is classified as a non-Collapsar if $T_{90} < 2$ s. Even though this criterion is based on the duration distribution of BATSE it is widely used for bursts detected by all satellites.

The fraction of Collapsars at short durations can be estimated by extrapolating the plateau in the duration distribution to short times. Since there is also an overlap with the SGRBs at long durations, the real heights of the plateaus are somewhat lower than what is shown in fig. 1. In Bromberg et al. (2011d) we make a joint fit of the non-Collapsars and the Collapsars by modeling the duration distribution of the non-Collapsars as well. The fitted distributions are then used to calculate the fraction f of the non-Collapsar from the total number of observed GRBs as a function of T_{90}. This fraction represents the probability that an observed GRB with a given duration in not a Collapsar. Fig. 2 depicts f as function of T_{90} for BATSE, *Swift* and Fermi GBM samples. Table 1 gives T_{90} at several selected values of this fraction. It can clearly be seen that using $T_{90} < 2$ s as a method to identify non-Collapsars works reasonably well for BATSE and is marginal in the case of Fermi, but in *Swift* data it results in a large over estimate of the number of non-Collapsars. Adopting, for example, $f = 0.5$ as the threshold fraction that separates the two populations, we find that for BATSE the transition occurs at ~ 3.5 s, for *Swift* it occurs at ~ 0.6 s and for Fermi at ~ 1.7 s (Note, however, that the errors in the Fermi data are quite large due to lack of statistics). This shift in the transition time is expected since non-Collapsars are on average harder than Collapsars and different detectors have different energy detection windows. BATSE has the hardest detection window, making it relatively more sensitive to non-Collapsar GRBs. *Swift* has the softest detection window making it relatively more sensitive to Collapsar GRBs.

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[4] HR is the fluence ratio between BATSE channels 3 (100-300 keV) and channel 2 (50-100 keV).
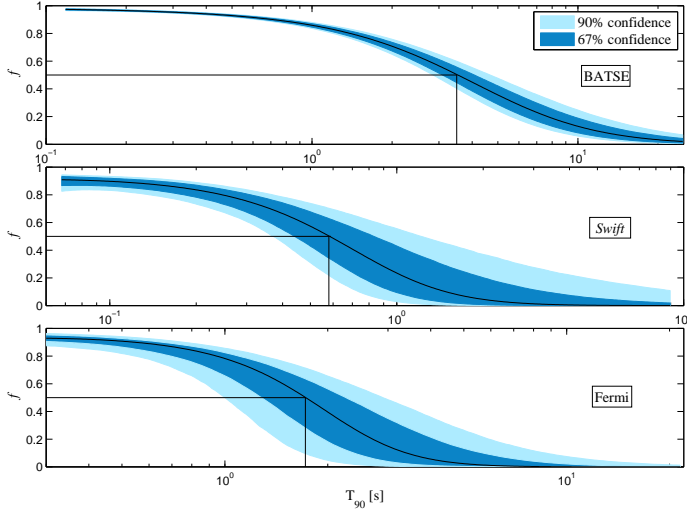
Figure 2: The fraction f of non-Collapsars from the total number of observed GRBs as a function of the observed duration time, T_{90}, in the (from top to bottom) BATSE, *Swift* & Fermi GBM samples. The shaded regions represent 67% and 90% confidence limits of f. Also plotted are the T_{90} for which $f = 0.5$ at each data set, the numerical values are given in table 1 (Bromberg et al., 2011d).

Satellite	$T_{90}(f = 0.5)[s]$	$T_{90}(f = 0.7)[s]$	$T_{90}(f = 0.9)[s]$
BATSE	3.5 ± 0.5	2 ± 0.2	0.7 ± 0.06
Swift	$0.6^{+0.2}_{-0.14}$	0.36 ± 0.09	$0.1^{+0.05\dagger}_{-0.04}$
Fermi	$1.7^{+0.6}_{-0.5}$	1.2 ± 0.3	$0.5^{+0.1\dagger}_{-0.2}$

† We restrict the analysis of *Swift* and Fermi data to $T_{90} > 0.06$ and 0.3 s respectively due to lack of statistics.

6. Discussion

The observed plateaus in all three duration distributions, and most notably in the distribution of soft BATSE bursts, provide a direct support for the Collapsars model for LGRBs. An inspection of different regions of the observed temporal distribution (Fig. 1), under the interpretation of the plateau as an imprint of the time it takes the jet to break out of the envelope, provides further important information.

1. The end of the plateau and the decrease in the number of GRBs at long durations, allow us to estimate the typical time it takes a jet to breakout of the progenitor's envelope. All three distributions are flat below ~ 10 s in the GRB frame, implying that $\hat{t}_b \sim$ a few dozen seconds. This fits nicely with the canonical GRB parameters used in Eq. 2.1, and provides another indication that the stellar progenitors of Collapsars must be compact (Matzner, 2003).

2. The distribution at long durations can be used to set a lower limit on the number of chocked jets, by extrapolating the slope at $T_{90} \gg \hat{t}_b$ to durations shorter than $\hat{t}_b$ (see section 3). At durations $T_{90} \gtrsim 100$ s p_γ can be fitted by a power law, $p_\gamma \propto T_{90}^\alpha$ with $-4 < \alpha < -3$. Extrapolating to $T_{90} < \hat{t}_b$ we find that if p_e continues with this power law to $t_e < \hat{t}_b$ there are significantly more chocked GRBs than long ones. For example, even if we extrapolate this distribution only down to $t_e = \hat{t}_b/2$ there are ~ 10 times more chocked GRBs than long GRBs. This prediction

is consistent with the suggestion that shock breakout from these choked GRBs produces low luminosity smooth and soft GRBs (Nakar & Sari, 2011, and references there in). Indeed the rate of such low luminosity GRBs is far larger than that of regular long GRBs (Soderberg et al., 2006).

3. At short durations, the duration distribution is dominated by non-Collapsars SGRBs. These bursts are hard to classify and are commonly defined by their shorter duration. Our analysis shows that putting the dividing line between Collapsars and non-Collapsars at 2 s is statistically reasonable for BATSE, and possibly also for Fermi bursts. However, it is clearly wrong to do so for *Swift*. We also calculate the probability as a function of T_{90} that a burst with a given T_{90} is not produced by a Collapsar.

4. While the difference in the lower limit of the plateaus is understood qualitatively as it depends on the spectral range of the detector, the variance in the upper limit is less obvious. It may reflect various selection effects in triggering algorithms. A more interesting possibility is that it reflects a physical origin, e.g. different satellites probing populations with different $\hat{t}_b$. This could be explored when the statistical sample of Fermi GBM becomes sufficiently large.

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