

Are low luminosity GRBs generated by relativistic jets?

Omer Bromberg¹, Ehud Nakar², Tsvi Piran¹

¹ Racah Institute of Physics, The Hebrew University, 91904 Jerusalem, Israel

² The Raymond and Berverly Sackler School of Physics and Astronomy,
Tel Aviv University, 69978 Tel Aviv, Israel

ABSTRACT

Low luminosity gamma-ray bursts (*ll*-GRBs) constitute a sub-class of gamma-ray bursts (GRBs) that plays a central role in the GRB-supernova connection. While *ll*-GRBs differ from typical long GRBs (LGRBs) in many aspects, they also share some common features. Therefore, the question whether the gamma-ray emission of *ll*-GRBs and LGRBs has a common origin is of great interest. Here we address this question by testing whether *ll*-GRBs, like LGRBs according to the Collapsar model, can be generated by relativistic jets that punch holes in the envelopes of their progenitor stars. The collapsar model predicts that the durations of most observed bursts will be comparable to, or longer than, the time it takes the jets to breakout of the star. We calculate the jet breakout times of *ll*-GRBs and compare them to the observed durations. We find that there is a significant excess of *ll*-GRBs with durations that are much shorter than the jet breakout time and that these are inconsistent with the Collapsar model. We conclude that the processes that dominate the gamma-ray emission of *ll*-GRBs and of LGRBs are most likely fundamentally different.

1. Introduction

According to the Collapsar model (Paczynski 1998; MacFadyen & Woosley 1999) the core collapse of a massive star results in the formation of a compact object, a black hole or a rapidly rotating neutron star. The compact object ejects a relativistic bipolar, baryon poor jet, along its rotation axis. The jet punctures the surrounding stellar envelope and it emits the observed γ -rays at a large distance from the star where the optical depth is small and the high energy photons can escape. This model, that is accepted as the standard model for long GRBs (LGRBs), explains naturally the association of some LGRBs with SNe, and their general emergence in star forming regions (see Woosley & Bloom 2006; Hjorth & Bloom 2011, for recent reviews).

A closer look at the members of the spectroscopically confirmed GRB/SN group (on which the GRB/SNe association hinges) reveals that four out of the six detected bursts: GRB980425 (SN1998bw), GRB031203 (SN2003lw), GRB060218 (SN2006aj) and GRB100316D (SN2010bh), are quite different than “normal” LGRBs (see §2): They are less luminous; have a smooth non-variable lightcurve, and show no evidence for a high energy power-law tail. Although only a handful of such bursts were observed, the small observable volume set by their low luminosity implies an event rate much higher than the rate of LGRBs pointing towards Earth (Coward 2005; Cobb et al. 2006; Pian et al. 2006; Soderberg et al. 2006a; Liang et al. 2007; Guetta & Della Valle 2007; Fan et al. 2011). The unique characteristics of these low luminosity GRBs (denoted hereafter *ll*-GRBs) suggest that they may be generated by a totally different process than most LGRBs. As such it is of great interest to check whether *ll*-GRBs can arise from Collapsars. Specifically we ask the question: can *ll*-GRBs be generated by relativistic jets that break out of their progenitor stars.

To answer this question we study, in §3, (following Bromberg et al. 2011; hereafter B11) the propagation of a relativistic jet in a stellar envelope. We obtain the minimal conditions required for the jet to break out of the star. Specifically, we estimate the minimal time that the central engine must power the jet for a successful crossing of the star. Using this minimal breakout time we examine the expected duration distributions of LGRBs, SGRBs and *ll*-GRBs (§4). We discuss the implications of this distribution on the origin of *ll*-GRBs in §5 and we summarize our results in §6.

2. The properties of *ll*-GRBs

ll-GRBs are characterized by isotropic equivalent luminosities, $10^{46} - 10^{48}$ erg/s, that are much lower than typical, $10^{51} - 10^{53}$ ergs/s, emitted by LGRBs. The durations range between ~ 10 sec to an hour (in an extreme case of GRB 060218), and the corresponding isotropic equivalent energies of $E_\gamma = 10^{48} -$ a few times 10^{49} ergs, are two to three orders of magnitude lower than those of typical LGRBs. Apart from the low-luminosity which defines this sub-group, *ll*-GRBs have a softer spectrum with typical peak energies significantly below the average of LGRBs and with no evidence of high energy tail. Finally, *ll*-GRBs’ lightcurves are smooth, each containing only a single pulse. Most *ll*-GRBs are accompanied by energetic broad line type Ic SNe with a strong radio emission. Radiation models ascribe the radio emission to a mildly relativistic shock moving ahead of the non-relativistic SN material (e.g. Kulkarni et al. 1998). Rebrightening episodes in the radio emission are commonly associated with additional supply of energy that refresh the shock, indicating the presence of an internal engine that can operate for long times (Li & Chevalier 1999). Finally, the afterglow of some

ll -GRBs also show indications for late time activity of such an engine (Soderberg et al. 2006a).

Due to their low luminosity, ll -GRBs are detected only from low redshifts ($z \lesssim 0.1$). With these redshifts, the four observed ll -GRBs imply an event rate of $230_{-190}^{+490} \text{ Gpc}^{-3}\text{yr}^{-1}$ (Soderberg et al. 2006a, see also Coward 2005; Cobb 2006; Liang et al. 2007; Guetta & Della Valle 2007; Fan et al. 2011), about 100-1000 times higher than the rate of LGRBs pointing toward earth (Coward 2005; Liang et al. 2007; Guetta & Della Valle 2007; Wanderman & Piran 2010). Soderberg et al. (2006a) estimated the rate of broad line Ibc SNe to be of the same order as the rate of ll -GRBs, implying that ll -GRBs cannot be significantly beamed and that they could very well be isotropic. Using the overall ratio of the rates of broad line type Ib,c SNe and ll -GRBs we find that the beaming factor of ll -GRBs is $\lesssim 10$, corresponding to opening angles $\gtrsim 30^\circ$.

The lack of bright, late time, radio emission from ll -GRBs strongly constrain the total energy of any relativistic outflow involved in these events (Waxman 2004; Soderberg, Frail, & Wieringa 2004; Soderberg et al. 2006b). Additionally statistical arguments rule out the possibility that ll -GRBs are regular LGRBs viewed at a large angle (e.g. Daigne & Mochkovitch 2007). Thus, if ll -GRBs are generated by relativistic jets these jets must be weak and have a large opening angle.

3. Jets Propagations in Stellar Envelopes

We review, briefly, the essential features of jet propagation in a stellar envelope (B11). Consider a cold relativistic jet with a power L_j and an initial opening angle θ_0 that is injected into a star. As the jet propagates it pushes the stellar material in front of it, leading to the formation of a double shock structure at the jet's front, the jet's head. The pressure of the shocked material is much higher than the pressure of the surrounding medium, thus matter that enters the head is heated and pushed sideways forming a pressurized cocoon surrounding the jet. The cocoon, in turns, applies a pressure on the jet and if the jet power is not too large it collimates the jet into a cylindrical shape. The material in the collimated jet remains relativistic and its Lorentz factor is $\Gamma_j \simeq \theta_0^{-1}$. The jet's head propagates, however, at a much lower velocity and it effectively dissipates all the jet's energy into the cocoon. Thus, in order for the jet to breakout, the engine must operate continually and supply power to the jet practically until the jet's head reaches the surface, at which stage the dissipation stops.

The jet propagation depends on the stellar density profile. Above the stellar core through a considerable fraction of the envelope, where the jet spends most of its propagation time,

the density can be approximated as a power law with an index $1.5 \lesssim \alpha \lesssim 3$. For all the relevant parameter regime in ll -GRBs and regular LGRBs the jet's head is sub relativistic throughout this region. In this non-relativistic limit the head's velocity, $\beta_h \ll 1$, satisfies:

$$\beta_h = \kappa \left(\frac{L_j}{t^2 \rho c^5 \theta_0^4} \right)^{1/5}, \quad (1)$$

where ρ is the density of the star at the position of the head, and κ is a constant of order unity that depends on the power-law index of the density profile (B11). As the head reaches the stellar edge, where the density drops sharply, it accelerates and for all practical purposes the jet can be considered as having escaped from the star. The stellar radius, $R = c \int_0^{t_B} \beta_h dt$, is, therefore, the breakout radius of the jet from the star. Using eq. (1) we obtain the breakout time:

$$t_B \simeq 30 \text{ sec} \cdot L_{47}^{-1/3} \theta_{10^\circ}^{4/3} R_{11}^{2/3} M_{15\odot}^{1/3}, \quad (2)$$

where L_{47} is the jet's power in units of 10^{47} erg/s; θ_{10° is the opening angle in units of 10° ; R_{11} is the stellar radius in units of 10^{11} cm and $M_{15\odot}$ is the stellar mass in units of 15 solar masses. Here we use an average density profile of $\rho \propto r^{-2.5}$. The result changes only slightly for different profiles.

As long as the jet propagates in the star, the head dissipates its energy into the cocoon. If the engine shuts off before t_B , i.e., before the head reaches the surface, the head will stall. The energy deposited by the jet into the cocoon at a time t is $L_j t$. Since $\beta_h \ll 1$, this implies that the minimal energy required for the jet to cross the star is $E_{min} \simeq L_j t_B$, giving:

$$E_{min} \simeq 3 \times 10^{48} \text{ ergs} \cdot L_{47}^{2/3} \theta_{10^\circ}^{4/3} R_{11}^{2/3} M_{15\odot}^{1/3}. \quad (3)$$

The estimates of the breakout time and minimal energy depend on the jet's properties inside the star, which are not observed directly. However we can relate them to the observed properties of the GRB. At late times, when the jet has evacuated a channel in the stellar envelope, its opening angle practically equals to the injection angle θ_0 . It can be shown that this holds, in a non trivial way, also at earlier time, just after the jet breaks out from the star. As there is no direct feedback between the jet that crosses the envelope and the central engine, the observed luminosity of the jet (after breakout) should be comparable to the jet's luminosity while it propagates in the stellar envelope. This allows us to estimate the jet breakout time using the observed GRB's prompt isotropic equivalent luminosity, L_γ and the observed opening angle, θ :

$$t_B \simeq 15 \text{ sec} \cdot \eta^{1/3} L_{\gamma,50}^{-1/3} \theta_{10^\circ}^{2/3} R_{11}^{2/3} M_{15\odot}^{1/3}, \quad (4)$$

where $L_\gamma = \eta L_j \frac{2}{1-\cos\theta_0}^1$ and η is the efficiency of converting the jet power to radiation. Fi-

¹Note that L_j is the luminosity of each one of the two jets.

nally, similar reasonings, namely the fact that the activity of the central engine is determined by the stellar core whose initial radius is $\sim 10^8$ cm while the propagation of the jet takes place on a much larger scale and is determined by the structure of the envelope which is only weakly coupled to the core’s mass (e.g. Crowther 2007, and references there in), suggest that the duration that the central engine operates, t_{eng} , should be independent of the jet breakout time.

4. *ll*-GRBs as Collapsars?

The duration of the prompt emission, approximated by the proper value of T_{90} , cannot be shorter than the time that the engine is active after the jet breakout. In most GRB models the two are equal and $T_{90} = t_{eng} - t_B$. As discussed earlier, within the Collapsar model t_{eng} and t_B are uncorrelated. This implies that without fine tuning we expect that only a small fractions of bursts should have $T_{90} \ll t_B$. Namely, it is unreasonable that generically the engine operates just long enough to let the jet break out of the star and then stops right after breakout. This is a direct implication of the Collapsar model and if *ll*-GRBs arise from Collapsars they should satisfy this condition.

To test the hypothesis that *ll*-GRBs are Collapsars we examine their duration distribution and compare it with the duration distribution of regular *Swift* LGRBs. Our sample contains the four observed *ll*-GRBs and the *Swift* LGRBs with measured redshifts. We calculate the isotropic equivalent luminosity of the *Swift* bursts by dividing the observed fluence in the BAT band (15-150 keV) with the observed T_{90} and correcting for redshift. The result is multiplied by 3 to account for the total energy radiated in all bands. We set $L_\gamma = 2 \cdot 10^{48}$, the highest luminosity among the four confirmed *ll*-GRBs, as a threshold luminosity and consider any burst with a lower luminosity to be a *ll*-GRB. We find one additional burst (GRB051109B) that matches the low luminosity criterion. Interestingly, apart from fulfilling the luminosity criterion, the light curve of this burst is also smooth and single peaked and no strong emission is detected in the 100-350 keV band, suggesting a relatively low spectral peak like in other *ll*-GRBs (Hullinger et al. 2005). As there are no records of a SN search in the error box of this burst during the time it could have been detected, we cannot rule out the existence of an associated SN. The bursts with $L_\gamma > 2 \cdot 10^{48}$ are considered as regular GRBs and are separated into LGRBs and SGRBs according to the standard criterion of whether T_{90} in the observer frame is above or below 2 sec.

For each burst with a given observed luminosity we calculate the expected jet breakout time from a $15M_\odot$ star with a radius of 10^{11} cm, assuming an opening angle of 10° . For the four *ll*-GRBs associated with SNe we use the mass estimates from the associated SN (see

table 1) and an opening angle of 30° . Finely, to estimate the jet power we use a radiative efficiency coefficient $\eta = 1/2$. Changing the progenitor radius between $5 \cdot 10^{10} - 5 \cdot 10^{11}$ cm and the radiative efficiency between $0.1 - 1$ doesn't significantly change our results.

Fig. 1 depicts the distributions of T_{90}/t_B of *ll*-GRB, SGRBs and LGRB. About 20% of LGRBs have $T_{90} < t_B$, in agreement with the expected small probability of having $t_{eng} \simeq t_B$ in a jet that successfully breaks out. All SGRBs are concentrated at low values of T_{90}/t_B with $T_{90} < 0.2t_B$. This is a manifestation of the well accepted concept that SGRBs cannot arise from a jet breakout and cannot result from Collapsars.

Although there are two *ll*-GRBs with $T_{90} > t_B$ the overall distribution of *ll*-GRB differs significantly from that of LGRBs and it closer to the distribution of SGRBs. In particular, 3 out of 5 *ll*-GRBs have $T_{90} < 0.25t_B$, while less than 4% of LGRBs are in this range. Using the K-S test we can estimate the chance that the observed duration distribution of *ll*-GRBs is taken from the LGRBs duration distribution. With such a few data points the standard χ^2 distribution doesn't give a good estimate for the probability to get a given K-S distance. To remedy this we use a Monte Carlo K-S to estimate this probability. We randomly drew 5 events from the LGRBs distribution and obtain the K-S distance between the simulated sample and the LGRBs distribution. We repeated this process 10^5 times and find that less than 5% of the randomly chosen events have larger K-S distance than the *ll*-GRB sample. This suggests that the origin of *ll*-GRBs is most likely different than that of LGRBs. In particular the large fraction of events with $T_{90} \ll t_B$ in the *ll*-GRB sample disfavors the successful jet break scenario.

Unlike the LGRB sample that contains only *Swift* bursts, the *ll*-GRBs sample includes bursts from three different detectors: *Swift*, INTEGRAL and BATSE,. This introduces selection effects that are hard to quantify. Nevertheless, there is no clear effect against detection of short duration ($T_{90} \ll t_B$), soft GRBs, by *Swift* or by the two other detectors. Since the discrepancy between *ll*-GRBs and LGRBs populations is dominated by such events, we do not expect the heterogenic composition of *ll*-GRBs sample to affect our conclusion.

The Collapsar model introduces two independent time scales, t_{eng} and t_B . This provides a simple way to quantify the expected T_{90} distribution for bursts with $T_{90} \ll t_B$ (Bromberg et al. 2011b). Let $p_{eng}(t_{eng})$ be the probability density for t_{eng} . Let t_B be a typical jet breakout time. The number of bursts per unit of duration time, T_{90} , is :

$$dN/dT_{90} = p_{eng}(T_{90} + t_B). \quad (5)$$

Assuming that p_{eng} is smooth and does not vary on short time scales in the vicinity of t_b , then for $T_{90} \ll t_B$, $dN/dT_{90} \simeq p_{eng}(t_B)$, which is a constant, independent of T_{90} . Indeed, the observed T_{90} distribution of LGRBs, satisfies this prediction, providing an additional

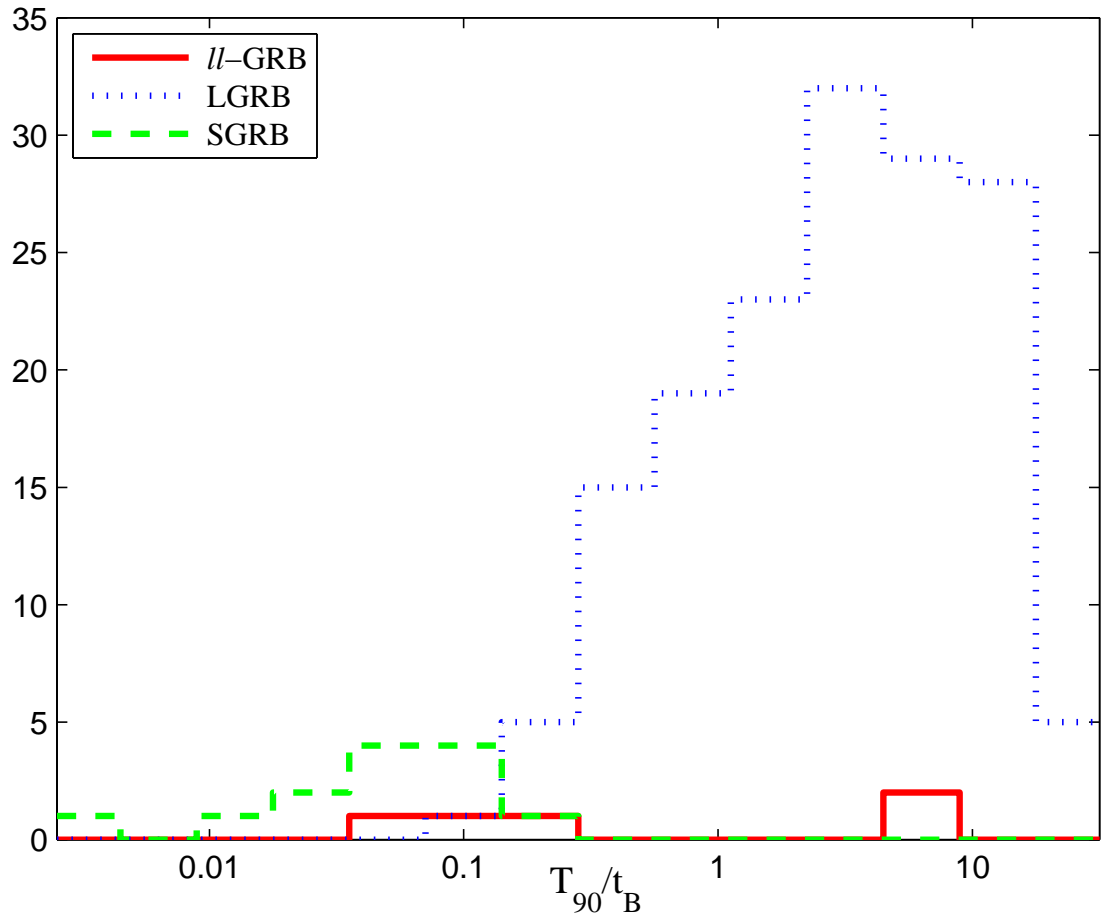


Fig. 1.— The distribution of T_{90}/t_B for LGRBs, *l*-GRBs, and SGRBs.

support to the Collapsar model (see Bromberg et al. 2011b, for a thorough discussion).

For a typical ll -GRB luminosity and for the observed progenitor stars that are implied by their SNe, the typical t_B is of order of $\gtrsim 200$ sec. There are two ll -GRB with $10 < T_{90} \lesssim 20$ sec. Thus for a flat distribution, we would expect ~ 20 with $20 \lesssim T_{90} \lesssim 200$ sec, where only one was observed. The probability that those three events are randomly selected from a flat distribution between 0 and 200 sec is $< 3\%$. This is in contrast to LGRBs where this distribution is flat (see Bromberg et al. 2011b) Even though the sample of the ll -GRBs is very small, the large fraction of bursts with $T_{90} \ll t_B$, combined with the lack of accompanied bursts with $T_{90} \sim t_B$, implies that it is highly unlikely that this distribution arises from Collapsars. While the statistical significance is lower, the reasoning leading to this conclusion is similar to the one that have lead to the realization that SGRBs cannot be produced by Collapsars.

Table 1:

GRB/SN	z	T_{90}^\dagger [s]	E_γ [ergs]	L_γ [erg/s]	M/M_\odot	T_{90}/t_B	ref
980425/1998bw	0.0085	23	$7 \cdot 10^{47}$	$3 \cdot 10^{46}$	14	0.05	1,2
031203/2003lw	0.105	30	$4 \cdot 10^{49}$	$1.3 \cdot 10^{48}$	13	0.23	3,4
051109B/ ?	0.08	14	$< 1.3 \cdot 10^{49}$	$< 9 \cdot 10^{47}$	(15) [‡]	< 0.09	5
060218/2006aj	0.033	2000	$6 \cdot 10^{49}$	$3 \cdot 10^{46}$	3.3	7	6,7
100316D/2010bh	0.0593	1200	$6 \cdot 10^{49}$	$5 \cdot 10^{46}$	2.2	6	8,9

† redshift corrected values

‡ assumed value due to lack of SN detection

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|--|----------------------------|--------------------------|
| 1)Galama et al. (1998) | 4)Mazzali et al. (2006a) | 7)Mazzali et al. (2006b) |
| 2)Nakamura et al. (2001) | 5)Troja et al. (2006) | 8)Starling et al. (2011) |
| 3)Sazonov, Lutovinov, & Sunyaev (2004) | 6)Soderberg et al. (2006a) | 9)Cano et al. (2011) |

5. The Origin of ll -GRBs

We have shown that it is quite unlikely that ll -GRBs are produced by jets punching holes in their progenitors’ stellar envelopes. While we cannot rule out that any specific ll -GRB was generated like that, the chances that the group as a whole operates in this manner are small. Still, both ll -GRBs and LGRBs are accompanied by a rare type of SNe, suggesting a strong connection between the two phenomena. Moreover, late observations of ll -GRBs accompanied SNe suggest that their progenitors harbor central engines (Li & Chevalier 1999;

Soderberg et al. 2006a).

The two concepts can be reconciled if ll -GRBs’ jets simply fail to breakout from their progenitors. A ”failed jet” dissipates all its energy into the surrounding cocoon and drives its expansion. As the cocoon reaches the edge of the star its forward shock may become mildly or even ultra relativistic emitting the observed γ -rays when it breaks out. This idea that ll -GRBs arise from shock breakouts is not new. It was suggested shortly following the observations of GRB980425/SN1998bw (Kulkarni et al. 1998; MacFadyen, Woosley, & Heger 2001; Tan, Matzner, & McKee 2001). It drew much more attention following the observation of additional ll -GRBs with similar properties and especially with the observation of a thermal component in the spectrum of ll -GRB 060218 (Campana et al. 2006; Wang et al. 2007; Waxman, Mészáros, & Campana 2007). Yet, it was hard to explain how shock breakout releases enough energy in the form of γ -rays. Katz, Budnik, & Waxman (2010) realized that the deviation of the breakout radiation from thermal equilibrium provides a natural explanation to the observed γ -rays. More recently, Nakar & Sari (2011) calculated the emission from mildly and ultra-relativistic shock breakouts, including the post breakout dynamics and gas-radiation coupling. They find that the total energy, spectral peak and duration of all ll -GRBs can be well explained by relativistic shock breakouts. Moreover, they find that such breakouts must satisfy a specific relation between the observed total energy, spectral peak and duration, and that all ll -GRBs satisfy this relation. These results lend a strong support to the idea that ll -GRBs are relativistic shock breakouts. From a historical point of view this understanding closes the loop with Colgate’s (1968) original idea, that preceded the detection of GRBs, that a SN shock breakout will produce a GRB.

In a relativistic shock breakout the burst duration is set by the properties of the shock and the envelope at the edge of the star and not by the activity time of the engine. Therefore, the engine may operate for only a short time, and still generate a very long burst like that of ll -GRBs 060218 and 100316D. Thus, both longer and shorter duration ll -GRBs may be generated by this mechanism.

6. Conclusions

The activity of the central engine, within the Collapsar model, is independent of the breakout time of the jet. This implies that the duration of the majority of bursts should be comparable to, or longer than, their jet breakout time and that for $T_{90} \ll t_B$ the bursts’ duration distribution should be constant, independent of T_{90} . These two predictions are satisfied by LGRBs, providing another support to the Collapsar model (Bromberg et al. 2011b). As expected, they are not satisfied by SGRBs that are not produced by Collapsars.

Like SGRBs, the observed distribution of ll -GRBs is inconsistent with these two predictions of the collapsar model. A large fraction of ll -GRBs has $T_{90}/t_B \ll 1$. The probability that the observed ll -GRBs T_{90}/t_B distribution is consistent with the LGRBs distribution is smaller than 5%. Similarly, the ll -GRBs T_{90} distribution (for $T_{90} \ll t_B$) is not flat at a confidence level $> 97\%$.

Taken together with their peculiar γ -ray emission, our overall conclusion is that ll -GRBs are very unlikely to be produced by Collapsars like LGRBs. This can be reconciled with the fact that ll -GRBs are accompanied by “engine driven” SNe, if ll -GRBs are produced by “failed jets” that don’t break out of their progenitors. These “failed” jets deposit their energy into the stellar envelopes and the γ -ray emission arises from shock breakout (Kulkarni et al. 1998; MacFadyen, Woosley, & Heger 2001; Tan, Matzner, & McKee 2001; Campana et al. 2006; Wang et al. 2007; Waxman, Mészáros, & Campana 2007; Katz, Budnik, & Waxman 2010; Nakar & Sari 2011). Our analysis doesn’t prove this model but it strongly disfavors its major competitor, any variant on the Collapsar model.

The conclusion that the ll -GRBs originate from “failed jets” rather than successful ones has some interesting implications. In particular the high rate of ll -GRBs implies that jets which are generated in SNe have a higher chance of remaining buried than to break out. Accordingly most SNe engines can generate jets that produce ll -GRB and only a few are powerful enough to produce jets that break out and produce LGRBs (Mazzali et al. 2008).

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REFERENCES

- Bromberg O., Nakar E., Piran T. & Sari R., 2011, Submitted to ApJ (B11).
- Bromberg O., Nakar E., Piran T. & Sari R., 2011, In prep..
- Campana S., et al., 2006, Natur, 442, 1008
- Cano Z., et al., 2011, arXiv, arXiv:1104.5141
- Cobb B. E., Bailyn C. D., van Dokkum P. G., Natarajan P., 2006, ApJ, 645, L113
- Colgate, S. A. 1968, Canadian Journal of Physics, 46, 476

- Coward D. M., 2005, MNRAS, 360, L77
- Crowther P. A., 2007, ARA&A, 45, 177
- Daigne F., Mochkovitch R., 2007, A&A, 465, 1
- Fan Y.-Z., Zhang B.-B., Xu D., Liang E.-W., Zhang B., 2011, ApJ, 726, 32
- Galama T. J., et al., 1998, ApJ, 497, L13
- Guetta D., Della Valle M., 2007, ApJ, 657, L73
- Hjorth J., Bloom J. S., 2011, arXiv, arXiv:1104.2274
- Hullinger D., et al., 2005, GCN, 4237, 1
- Katz B., Budnik R., Waxman E., 2010,
- Kulkarni S. R., et al., 1998, Natur, 395, 663
- Li Z.-Y., Chevalier R. A., 1999, ApJ, 526, 716
- Liang E., Zhang B., Virgili F., Dai Z. G., 2007, ApJ, 662, 1111
- MacFadyen A. I., Woosley S. E., 1999, ApJ, 524, 262
- MacFadyen A. I., Woosley S. E., Heger A., 2001, ApJ, 550, 410
- Matzner C. D., McKee C. F., 1999, ApJ, 510, 379
- Mazzali P. A., et al., 2003, ApJ, 599, L95
- Mazzali P. A., et al., 2006a, ApJ, 645, 1323
- Mazzali P. A., et al., 2006b, Natur, 442, 1018
- Mazzali P. A., et al., 2008, Sci, 321, 1185
- Nakamura T., Mazzali P. A., Nomoto K., Iwamoto K., 2001, ApJ, 550, 991
- Nakar E., Sari R., 2011, submitted to ApJ.
- Paczynski B., 1998, ApJ, 494, L45
- Pian E., et al., 2006, Natur, 442, 1011
- Sazonov S. Y., Lutovinov A. A., Sunyaev R. A., 2004, Natur, 430, 646

- Soderberg A. M., Frail D. A., Wieringa M. H., 2004a, ApJ, 607, L13
- Soderberg A. M., et al., 2006a, Natur, 442,1014
- Soderberg A. M., Nakar E., Berger E., Kulkarni S. R., 2006b, ApJ, 638, 930
- Starling R. L. C., et al., 2011, MNRAS, 411, 2792
- Tan J. C., Matzner C. D., McKee C. F., 2001, ApJ, 551, 946
- Troja E., Cusumano G., Laparola V., Mangano V., Mineo T., 2006, NCimB, 121, 1599
- Wanderman D., Piran T., 2010, MNRAS, 406, 1944
- Wang X.-Y., Li Z., Waxman E., Mészáros P., 2007, ApJ, 664, 1026
- Waxman E., 2004, ApJ, 602, 886
- Waxman E., Mészáros P., Campana S., 2007, ApJ, 667, 351
- Woosley S. E., Bloom J. S., 2006, ARA&A, 44, 507