# EVIDENCE FOR A FAST DECLINE IN THE PROGENITOR POPULATION OF GAMMA RAY BURSTS AND THEIR LUMINOSITY FUNCTION

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We show that the source population of long gamma-ray bursts (GRBs) has declined by at least a factor of 12 (at the 90% confidence level) since the early stages of the Universe ($z \sim 2-3$). This result has been obtained using the combined BATSE and *Ulysses* GRB brightness distribution and the detection of four GRBs with known redshifts brighter than $10^{52}$ erg s$^{-1}$ in the 50 - 300 keV range at their peak. The data indicate that the decline of the GRB source population is as fast as, or even faster than, the measured decline of the star formation rate. Models for the evolution of neutron star binaries predict a significantly larger number of apparently bright GRBs than observed. Thus our results give independent support to the hypernova model, which naturally explains the fast decline in the progenitor population. The luminosity function of GRBs is close to a power law, $dN/dL \sim L^{-1.5}$, for low luminosities over at least 1.7 orders of magnitude. Then the luminosity function breaks to a steeper slope or to an exponential decline around $L \sim 3 \cdot 10^{51}$ erg s$^{-1}$ in the 50 - 300 keV range assuming isotropic emission.

## 1 Introduction

The cosmological evolution of GRB progenitors at redshifts $z < 2$ can, in principle, reveal their nature. Indeed, we have unambiguous star formation data (hereafter SF; see Porciani & Madau 2001 and references therein) for the declining stage which started after $z \sim 2$, which we can use as a reference evolutionary curve. If GRB progenitors follow this curve or decline even faster than it, then we have to conclude that GRBs are most probably associated with the collapse of supermassive stars (hypernovae, as originally suggested by Woosley 1993, see also Paczynski 1998 and MacFadyen & Woosley 1999). If the decline of GRBs is slower than the SF decrease then the coalescing neutron star binary model would be supported, as it naturally provides a delay between star formation and bursts.

The problem of deriving the GRB source evolution from the data is not simple and cannot be solved by a straightforward cosmological fit to the log N - log P distribution with an unknown GRB luminosity function. Despite the wealth of statistics on GRBs accumulated by the Burst and Transient Source Experiment (BATSE) aboard the *Compton Gamma-Ray Observatory* (see Fishman et al. 1989), the bright end of the distribution still contains too few events to provide a conclusive $\chi^2$ fit. For a review of cosmological fits to the log N - log P distribution see, e.g., Bulik (1999).

In this work we incorporate all statistically important GRB data in order to derive the GRBs luminosity function and source evolution and to achieve a scientifically meaningful constraint on the NS binary model.

## 2 The data

We have used three independent data sets. The first contains 3255 BATSE GRBs with durations longer than 1 s, found by Stern et al. (2001) in the off-line scan of the 1.024 s time resolution BATSE continuous daily records for the entire 9.1 yr BATSE mission [f]. This is the largest essentially uniform GRB sample, and its efficiency matrix has been measured using a test burst method. The second data set is the *Ulysses* sample, consisting of only bright GRBs, which are the most important ones for the aim of the present work. The *Ulysses* GRB detector has amassed well over 10 years of data to date, and since the detector is in interplanetary space and is neither Earth- nor spacecraft-occulted, it has $\approx 4\pi$ sr sky exposure and a larger effective duty cycle than BATSE (useful data are recovered for more than 95% of the mission), thus more then doubling the number of bright GRBs. The *Ulysses* GRB data on over 800 bursts have appeared in eight catalogs so far (Hurley et al. 1999a,b; Laros et al. 1997, 1998; Hurley et al., 2000a,b,c; Hurley et al. 2001a); the instrument description may be found in Hurley et al. (1992). The third data set consists of the GRB redshift data, or more specifically the data on the four intrinsically brightest events out of 23 GRBs with measured redshifts (up to November 2001)[g] .

The first two data sets were cross-calibrated using common BATSE/Ulysses events and combined to form a single log N - log P distribution, i.e. the number of events versus the *apparent* peak brightness, $P_a$, while the third data set was used to constrain the hypothetical *intrinsic* peak brightness ($P_i$) distribution (the luminosity function).

The sample of events with known redshift is subject to strong brightness selection biases and cannot be used directly to determine the luminosity function. It, however, gives useful information about the existence of intrinsically very bright GRBs. We can use this fact to constrain the bright end of the hypothetical luminosity function: the predicted rate of GRBs with $P_i$ above some threshold at all redshifts should correspond to the observed rate. This constraint will affect the predicted number of apparently bright GRBs and therefore constrain the GRB source evolution model.

There are 4 very bright GRBs with known redshifts detected over 4.2 years of observations from the beginning of 1997 to Marh 2001. Their absolute peak brightness exceeds $10^{52}$erg/s We can estimate their sampling factor, i.e. the probability that the burst will be detected and localized, its afterglow observed and its redshift measured using aparrently bright Ulysses events. Taking all *Ulysses* GRBs with peak count rates above 370 $s^{-1}$ which corresponds to approximately 15 photons $s^{-1}$ $cm^{-2}$ (62 events from 1997 January 1 to 2001 March 1) we find redshift data for 4 of them (two of which are among four intrinsically bright GRBs mentioned above). Using these numbers we estimate the sampling factor as $F_s \sim 0.064^{+0.038}_{-0.026}$. Taking the $1\sigma$

[f] see http://www.astro.su.se/groups/head/grb_archive.html
[g] see, e.g., http://www.aip.de/ jcg/grb.html

upper limit, 0.1, as a conservative estimate we obtain the rate of detectable intrinsically bright GRBs $I_{52} \sim 10$/year. We adopt this estimate as our baseline and, to take the poor statistics into account, we also rederive all our results for $I_{52} = 4$/year. Future observations will show which value is closer to reality.

## 3 Fitting Models

The fitting model consists of three independent components: the cosmology, the evolution of the GRB source population, and the intrinsic luminosity function (hereafter just luminosity function or LF).

The cosmological model is not very important for the purpose of the present work as it affects only large redshifts while the main issue we are concerned with here is the source evolution at low redshifts. We adopted a flat vacuum-dominated cosmology ($\Omega_\Lambda = 0.7, \Omega_M = 0.3$) which is supported by recent data (see, e.g., Lukash, 2000).

The evolution of the source population is the objective of our study. We tested four evolutionary functions. The first is a non-evolving population (NE). The second is the star formation function, which is a reasonable hypothesis for the evolution of GRB progenitors if they are collapsars. Porciani & Madau (2001) suggest three parameterized versions of the star formation rate. We use one of them, describing a constant SF rate at large redshifts:

$$R_{SF}(z) = \frac{0.15e^{3.4z}}{(e^{3.4z}+22)} \quad \mathrm{M_\odot yr^{-1} Mpc^{-3}} \tag{1}$$

The two other evolution functions used correspond to neutron star merger models. We obtained them by convolving the above SF rate with two different distributions for the delay between the formation of a binary system and the coalescence of its daughter neutron star binary. The first delay distribution was taken from Lipunov et al. (1995), hearafter L95, and the second from Portegies-Zwart & Yungelson (1998), hereafter PZY98. These distributions are quite different from one another. L95 predicts a peak at delays of 10 - 20 Myr and a long tail with a comparatively high probability of several Gyr delays. The distribution of PZY98 has a maximum around 1 Gyr and lower probability at several Gyr. In addition to four fixed evolution models we tested different slopes of the decline phase of the source population, modifying Eq. (1) as

$$R_{SF}(z) \propto \frac{e^{1.086 ln(a+1)z}}{(e^{1.086 ln(a+1)z}+a)} \tag{2}$$

where $a$ is a parameter describing the fall-off with redshift. The expression coincides with (1) at $a = 22$.

The third component of the model is the hypothetical luminosity function. The data allow a wide choice with only two constraints: the width of the function, which must be at least 2.5 orders of magnitude (the luminosity range of GRBs with measured $z$), and the number of intrinsically bright GRBs (see section 2). In order to get a handle on the ILF of GRBs, we tried different types of functions that describe common shapes of wide distributions in nature: the log-normal distribution (LGN), a truncated power law (TPL), a power law with an exponential cutoff (PLexp), and a broken power law (BPL).

We used the forward folding method when fitting GRB data, i.e., the hypothetical brightness distribution was convolved with the efficiency matrix and fitted to the observed differential log N - log P distribution represented by 28 data points below $P = 50$ photons s$^{-1}$ cm$^{-2}$. In 9.1 years of BATSE and *Ulysses* data, there were 15 GRBs brighter than this. We treat the range $P > 50$ photons s$^{-1}$ cm$^{-2}$ separately, estimating the likelihood function of the fit for each peak flux range. For the main interval, this is the standard $\chi^2$ probability function. For the tail of the brightness distribution, the likelihood is the Poisson probability of finding no more than 15 events apparently brighter than 50 photons $s^{-1}$ $cm^{-2}$ assuming an average number $A_{50}$ predicted by the model.

## 4 Results

The results of the fit with different evolution models with BPL luminosity function are given in Table 1. The best fit integral log N - log P distributions for the four models, SF, PZY98, L95, and NE are shown in Figure 1.

| Model | lkh | $\chi^2$ | $A_{50}$ | lkh($A_{50}$) | U lkh |
|---|---|---|---|---|---|
| NE | $3.8 \cdot 10^{-13}$ | 83 | 49 | $1.28 \cdot 10^{-8}$ | $1.3 \cdot 10^{-5}$ |
| $SF_{22}$ | 0.034 | 31 | 18.6 | 0.24 | 0.052 |
| L85 | $1.9 \cdot 10^{-5}$ | 37 | 33 | $2.1 \cdot 10^{-4}$ | 0.022 |
| PZY98 | $1.9 \cdot 10^{-3}$ | 32 | 26 | $1.4 \cdot 10^{-2}$ | 0.021 |
| $SF_{80}$ | 0.088 | 31 | 15 | 0.57 | 0.088 |
| $SF_{40}$ | 0.062 | 31 | 16 | 0.47 | 0.062 |
| $SF_{10}$ | $0.36 \cdot 10^{-2}$ | 31 | 25 | $2.2 \cdot 10^{-2}$ | 0.018 |
| $SF_5$ | $0.76 \cdot 10^{-4}$ | 38 | 30 | $1.9 \cdot 10^{-3}$ | 0.0039 |

**Table1** The maximum likelihood results for various models. The second column (lkh) gives the final likelihood factor; the third column, the $\chi^2$ value (at 24 degrees of freedom); the fourth, the predicted $A_{50}$ (the observed $A_{50}$ is 15); the fifth, the probability of observing $A_{50}$ less than 16 for its predicted value. The sixth column gives the likelihood for the best fit models without the constraint resulting from redshift data. The subscripts in the first column correspond to the value of $a$ (see equation 2). $SF_{22}$ in row 2 corresponds to the measured star formation curve.

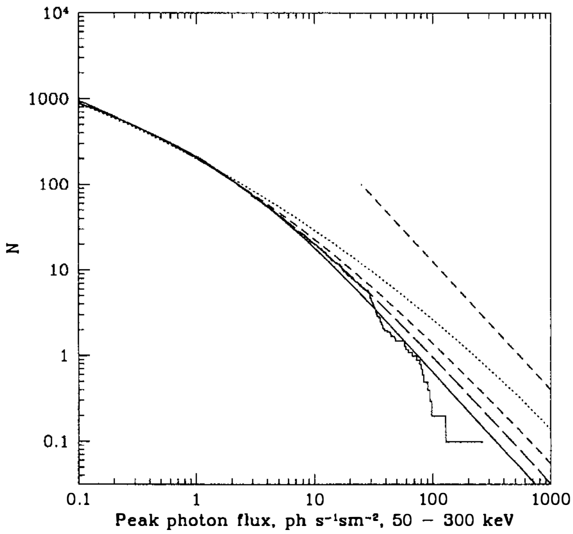


**Figure 1.** Comparison between the predictions of different evolutionary models and the data in integral form. Histogram: the integral peak flux distribution of *Ulysses* /BATSE GRBs; solid curve: SF model; dotted curve: NE; dashed curve: L95; long dashed curve: PZY98.

If we use the Bayesian approach, treating the ratio of likelihoods as the relative probabilities of different models, then the rejection factors for NS models relative to SF are 0.055 for PZY98 and $1.3 \cdot 10^{-3}$ for L95. If we adopt the estimate $I_{52} = 4$ (instead of $I_{52} = 10$ then the constraints relax to 0.37 and 0.024 respectively, i.e. the PZY98 model is consistent with the data. Note however that the choice of $I_{40} = 4$ corresponds to a less than 0.1 probablity fluctuation in the number of intrinsically bright GRBs with measured redshifts.

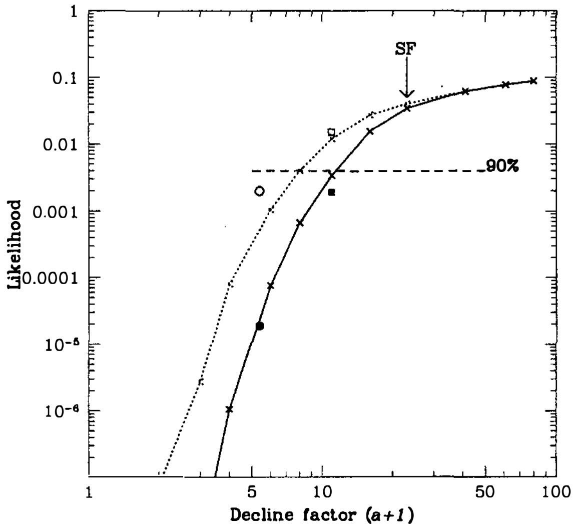


**Figure 2**. The likelihood versus the fall-off factor $(a + 1)$ where $a$ is the parameter in equation 2. The arrow shows the result for the SF model; the 90% confidence limit (dashed horizontal line) is given with respect to this model.

Figure 2 shows the likelihood factor for the parametrized source evolution model (equation 2) versus the fall-off factor $a + 1$. The results for NS merger models are also shown; the ordinate for these models is just the ratio of the maximal NS merging rate (at $z \sim 2$) to that at $z = 0$. The likelihood curve has no turnover at large $a$ because our luminosity function has only a lower limit constraint at its bright end. It is interesting that the curve still displays a considerable increase (by a factor of 2.6) from $a$=22, which corresponds to the SF curve, to $a = 80$, i.e., the data are better fit by a GRB progenitor fall-off which is faster than the SF rate. This could be a natural consequence if the progenitors are supermassive stars whose population can decline faster than the total SF. However, this indication is statistically weak.

Describing the luminosity function we concentrate on the SF model. There are two clear features of the LF that are required by data: a near power law interval at the lower brightness range and a break or exponential turnover towards the bright end of the distribution (PLexp luminosity function fits the data with the same likelihood as BPL). Attempting to replace this construction of the LF by a log-normal LF gives a decrease of the maximum likelihood by 2 orders of magnitude. A break or a turnover is necessary at a high significance level. Its removal increases $\chi^2$ by 25 for SF model.

The properties of the break are, however, less certain than the parameters of the power law fragment. All we can say is that some turnover in the power law LF is required at an intrinsic brightness of about 10 photons $s^{-1}$ $cm^{-2}$ at $z = 1$, or $\sim 3 \cdot 10^{51}$ erg $s^{-1}$ for isotropic emission.

If we study the $\chi^2$ topography for the broken power law LF, we find a power law fragment at least 1.7 orders of magnitudes wide and there is no upper limit on its width.

## 5 Conclusions

The joint BATSE - *Ulysses* data confirm a sharp decline in the GRB source population between $z \sim 2$ and the present epoch. Although it is consistent with that of star formation, a faster decline is slightly preferable, albeit at a statistically insignificant level ($\sim 1\sigma$). The two models of binary system evolution leading to a final NS merger are well beyond the 90% confidence limit, except for the $I_{52} = 4$ case, which is based on the assumption of a large fluctuation in the observed number of intrinsically bright GRBs. Note that while the statistics of bright GRBs will improve slowly, the redshift statistics can improve much faster, so that a more reliable estimate of $I_{52}$ may be available relatively soon.

The joint BATSE/*Ulysses* data present a new challenge to the neuton star binary model as an explanation of the source of long GRBs. Together with the results of afterglow studies it makes it very improbable. The only way to save the NS model is to show that the typical lifetimes of such systems is short. If very few survive longer than 1 Gyr, this will fit the log N - log P distribution, and if many merge in a few Myr, this will explain the locations of the observed afterglows in the star forming regions of their host galaxies. Such a possibility has been studied in the recent work of Belczynski, Bulik & Rudak (2001) where it is shown that this could occur in some binary evolution models due to common envelope events producing very tight NS systems. Finally it should be pointed out again that our constraints refer only to the class of long GRBs, while the NS binary model is probably able to explain the origin of short bursts.

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