Evidence for luminosity evolution of long gamma-ray bursts in Swift data

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ABSTRACT

We compute the luminosity function (LF) and the formation rate of long gamma-ray bursts (GRBs) by fitting the observed differential peak flux distribution obtained by the Burst and Transient Source Experiment (BATSE) in two different scenarios: (i) the GRB luminosity evolves with redshift and (ii) GRBs form preferentially in low-metallicity environments. In both cases, model predictions are consistent with the Swift number counts and with the number of detections at \( z > 2.5 \) and \( > 3.5 \). To discriminate between the two evolutionary scenarios, we compare the model results with the number of luminous bursts (i.e. with isotropic peak luminosity in excess of \( 10^{53} \text{ erg s}^{-1} \)) detected by Swift in its first 3 yr of mission. Our sample conservatively contains only bursts with good redshift determination and measured peak energy. We find that pure luminosity evolution models can account for the number of sure identifications. In the case of a pure density evolution scenario, models with \( Z_{\text{th}} > 0.3 Z_\odot \) are ruled out with high confidence. For lower metallicity thresholds, the model results are still statistically consistent with available lower limits. However, many factors can increase the discrepancy between model results and data, indicating that some luminosity evolution in the GRB LF may be needed also for such low values of \( Z_{\text{th}} \). Finally, using these new constraints, we derive robust upper limits on the bright end of the GRB LF, showing that this cannot be steeper than \( \sim 2.6 \).

Key words: stars: formation – cosmology: observations – gamma-rays: bursts.

1 INTRODUCTION

Gamma-ray bursts (GRBs) are powerful flashes of high-energy photons occurring at an average rate of a few per day throughout the universe. Their luminosity is such that they can be detected up to very high redshift (the current record is GRB 080913 at \( z = 6.7 \); Greiner et al. 2009). The energy source of a GRB is believed to be associated to the collapse of the core of a massive star in the case of long-duration GRBs, and due to merger- or accretion-induced collapse for the short-hard class of GRBs (see Mészáros 2006, for a recent review). In this paper, we limit our analysis to the class of long-duration GRBs.

The knowledge of GRBs has enormously benefited from the observations of the Swift satellite (Gehrels et al. 2004). Although the current sample of GRBs with known redshift is still too poor to allow a direct measure of the GRB luminosity function (LF), important constraints on the cosmic evolution of these sources can be set on the basis of recent Swift results. In particular, Salvaterra & Chincarini (2007, hereafter SC07) showed that models in which GRBs are unbiased tracer of cosmic star formation and are characterized by a constant LF are robustly ruled out by the number of GRB detections at \( z > 2.5 \) and \( > 3.5 \). Similar conclusions were reached recently by other studies (e.g. Guetta, Piran & Waxman 2005; Daigne, Rossi & Mochkovitch 2006; Cen & Fang 2007; Kistler et al. 2008). Moreover, they have shown that Swift data can be reproduced assuming luminosity evolution of the GRB LF (see also Lloyd-Ronning, Fryer & Ramirez-Ruiz 2002; Wei & Gao 2003; Daigne, Rossi & Mochkovitch 2006) and/or that GRBs form preferentially in low-metallicity environments (see also Natarajan et al. 2005; Langer & Norman 2006; Cen & Fang 2007; Lapi et al. 2008; Li 2008).

In this paper, we derive the formation efficiency and the free parameters describing the GRB LF by fitting the differential peak flux distribution of Burst and Transient Source Experiment (BATSE) GRBs in these two scenarios. We then obtain new and tighter constraints on the cosmic evolution of long GRBs by comparing different models against the number of luminous (i.e. with isotropic peak luminosities \( L \gtrsim 10^{53} \text{ erg s}^{-1} \)) GRBs detected by Swift. We also consider models with joint luminosity and density evolution providing a robust upper limit on the steepness of the bright end of the GRB LF.

This paper is organized as follows. In Section 2, we briefly describe the different models and the main equations used in the calculation of the LF, and in Section 3, we compare model results against Swift data. Finally, we summarize our findings in Section 4.
2 MODEL DESCRIPTION

The observed photon flux, $P$, in the energy band, $E_{\text{min}} < E < E_{\text{max}}$, emitted by an isotropically radiating source at redshift $z$ is

$$P = \frac{(1+z)\int_{E_{\text{min}}}^{E_{\text{max}}} S(E) dE}{4\pi d_L^2(z)},$$  

(1)

where $S(E)$ is the differential rest-frame photon luminosity of the source, and $d_L(z)$ is the luminosity distance. To describe the typical burst spectrum we adopt the functional form proposed by Band et al. (1993), i.e. a smoothly broken power law with a low-energy spectral index $\alpha$, a high-energy spectral index $\beta$ and a break energy $E_b = (\alpha - \beta) E_p / (\alpha + \beta)$, with $\alpha = -1$ and $\beta = -2.25$ (Preece et al. 2000; Kaneko et al. 2006). The spectrum normalization is obtained by imposing that the isotropic equivalent peak luminosity is $L = \int_{1\text{keV}}^{10000\text{eV}} E S(E) dE$. In order to broadly estimate the peak energy of the spectrum, $E_p$, for a given $L$, we assumed the validity of the correlation between $E_p$ and $L$ (Yonetoku et al. 2004; Ghirlanda et al. 2005), which is basically a different expression of the $E_p$-$L_{\text{iso}}$ relation (Amati et al. 2002; Amati 2006):

$$E_p = 337 \text{keV} \left( \frac{L}{2 \times 10^{52} \text{erg s}^{-1}} \right)^{0.49}.$$  

(2)

Although the above correlation has an appreciable scatter, we will show that this does not affect our results.

Given a normalized GRB LF, $\phi(L)$, the observed rate of bursts with peak flux between $P_1$ and $P_2$ is

$$\frac{dN}{dP} (P_1 < P < P_2) = \int_0^{\infty} \frac{dV(z)}{dz} \frac{\Delta \Omega}{4\pi} \frac{\Psi_{\text{GRB}}(z)}{1+z} \left( \int_{L(P_1,z)}^{L(P_2,z)} dL' \phi(L') \right),$$  

(3)

where $dV(z)/dz = 4\pi c d_L(z) / [H(z)(1+z)^2]$ is the comoving volume element,\(^1\) and $H(z) = H_0 [\Omega_M (1+z)^3 + \Omega_{\Lambda} + (1 - \Omega_M - \Omega_{\Lambda})(1+z)^{-1}]^{1/2}$. $\Delta \Omega$ is the solid angle covered on the sky by the survey, and the factor $(1+z)^{-1}$ accounts for cosmological time dilation. Finally, $\Psi_{\text{GRB}}(z)$ is the comoving burst formation rate. In this work, we model the GRB LF with a power law with an exponential cut-off at low luminosities:

$$\phi(L) \propto \left( \frac{L}{L_{\text{cut}}} \right)^{-\xi} \exp \left( -\frac{L}{L_{\text{cut}}} \right).$$  

(4)

SC07 have shown that models in which GRB form proportionately to the star formation rate (SFR) and are described by a LF constant in redshift are robustly ruled out by the number of GRB with sure detection at $z > 2.5$ and $>3.5$ during the first 2 yr of Swift mission. Thus, GRBs should have experienced some kind of evolution, becoming more luminous or more common in the past. Therefore, we consider here two families of models: (i) luminosity evolution models, where the cut-off luminosity in the GRB LF varies as $L_{\text{cut}} = L_0 (1+z)^\delta$ and (ii) density evolution models, where GRBs form preferentially in galaxies with metallicity below a given threshold $Z_0$. In the first case, the GRB formation rate is simply proportional to the global SFR, i.e. $\Psi_{\text{GRB}}(z) = k_{\text{GRB}} \Psi_{\star}(z)$. We use here the recent determination of the SFR obtained by Hopkins & Beacom (2006), slightly modified to match the observed decline of the SFR with $(1+z)^{-3}$ at $Z > 3$ suggested by recent deep-field data (Stark et al. 2006). For the density evolution models, the GRB formation rate is obtained by convolving the observed SFR with the fraction of galaxies at redshift $z$ with metallicity below $Z_0$ using the expression computed by Langer & Norman (2006). In this scenario, the cut-off luminosity is assumed to be constant in redshift, i.e. $L_{\text{cut}} = \text{const} = L_0$.

Furthermore, we consider a third family of models in which both effects are present: GRBs form preferentially in environments with $Z \leq Z_0$ and are characterized by an evolving LF.

3 LUMINOSITY VERSUS DENSITY EVOLUTION

The free parameters in our model are the GRB formation efficiency $k_{\text{GRB}}$, the cut-off luminosity at $z = 0$, $L_0$, and the LF power index $\xi$. We optimized the value of these parameters by $\chi^2$ minimization over the observed differential number counts in the $50$–$300$ keV band of BATSE. We use here the results by Stern et al. (2000), who considered both triggered and non-triggered bursts and also corrected the distribution taking into account the BATSE detector efficiency. The best-fitting parameters are reported in Table 1. As already pointed out by SC07, it is always possible to find a good agreement between models and data. Moreover, it is possible to reproduce also the differential peak flux count distribution in the $15$–$150$ keV Swift band using the same GRB LF and formation efficiency obtained by fitting the BATSE data. Consistently with SC07, we find that the number of GRBs confirmed at $z > 2.5$ and $>3.5$ in the 3 yr of Swift mission requires some kind of evolution. The results are shown in Fig. 1 for different evolution models. As a comparison, we show also the result for the no-evolution model with the solid thin line. The chance probability associated to the no-evolution model is found to be less than $10^{-4}$ ensuring that this kind of model can be discarded at a very high confidence level and indicating the need of some kind of evolution to explain Swift high-$z$ detections (see also SC07).

In this work we highlight a new tool to discriminate between these two evolution scenarios by computing the number of luminous GRBs, i.e. bursts with isotropic peak luminosity $L \geq 10^{53}$ erg s$^{-1}$ in the $1$–$10000$ keV band. The model predictions are obtained by

$$\frac{dN}{dL}(>L) = \int_0^{\infty} \frac{dV(z)}{dz} \frac{\Delta \Omega}{4\pi} \frac{\Psi_{\text{GRB}}(z)}{1+z} \int_{L_{\text{cut}}(z)}^{\infty} dL' \phi(L').$$  

(5)

where $L_{\text{cut}}(z) = \max \{ L, L_{0,\text{at}}(z) \}$ and $L_{0,\text{at}}(z)$ is the minimum luminosity of a burst exploding at redshift $z$ able to trigger Swift.

| Table 1. Best-fitting parameters for different models: top panel for pure luminosity evolution and bottom panel for pure density evolution. Errors are at 1σ level. |
|---|
| Pure luminosity evolution models | $\delta$ | $k_{\text{GRB}} (10^{-8} \text{M}^{-1} \odot)$ | $L_0 / (10^{51} \text{erg s}^{-1})$ | $\xi$ | $\chi^2_{\nu}$ |
|---|
| 1.5 | 1.07 ± 0.11 | 0.66 ± 0.21 | 2.16 ± 0.09 | 0.95 |
| 2.0 | 1.01 ± 0.10 | 0.36 ± 0.08 | 2.08 ± 0.06 | 0.83 |
| 2.5 | 0.94 ± 0.09 | 0.20 ± 0.04 | 2.03 ± 0.05 | 0.92 |
| 3.0 | 0.94 ± 0.09 | 0.10 ± 0.02 | 1.99 ± 0.04 | 0.84 |
|---|
| Pure density evolution models | $Z_{\text{th}} / (Z_\odot)$ | $k_{\text{GRB}} (10^{-8} \text{M}^{-1} \odot)$ | $L_0 / (10^{51} \text{erg s}^{-1})$ | $\xi$ | $\chi^2_{\nu}$ |
| 0.1 | 11.38 ± 1.60 | 10.34 ± 4.10 | 2.51 ± 0.22 | 0.81 |
| 0.2 | 4.45 ± 0.68 | 8.40 ± 3.58 | 2.48 ± 0.22 | 0.78 |
| 0.3 | 2.80 ± 0.45 | 7.40 ± 3.11 | 2.50 ± 0.22 | 0.80 |

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\(^1\) We adopted the ‘concordance’ model values for the cosmological parameters: $\delta = 0.7$, $\Omega_{\text{m}} = 0.3$ and $\Omega_{\Lambda} = 0.7$. 

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Figure 1. Cumulative number of GRBs at $z > 2.5$ (left-hand panels) and $z > 3.5$ (right-hand panels) as a function of the photon flux $P$. The no-evolution case is shown with the solid thin line. Top panels refer to luminosity evolution models: solid line is for $\delta = 3$, dotted line for $\delta = 2.5$, short-dashed line for $\delta = 2$ and long-dashed line for $\delta = 1.5$. Bottom panels refer to density evolution models: solid line is for $Z_0 = 0.1 Z_\odot$, dotted line is for $Z_0 = 0.2 Z_\odot$ and short-dashed line is for $Z_0 = 0.3 Z_\odot$. The number of bursts detected by Swift in 3 yr is shown as solid histogram. Note that the observed detections are lower limits, since many high-$z$ GRBs can be missed by optical follow-up searches. A field of view of 1.4 sr for Swift/BAT is adopted.

Figure 2. The cumulative number of luminous GRBs detected by Swift in 3 yr of operations is shown with the histogram as a function of the isotropic equivalent peak luminosity, $L$. Shaded area takes into account the errors on the determination of $L$. Note that the data are to be considered as lower limits of the real number of Swift detections, since only bursts with measured redshift and peak energy are included in our sample. Pure luminosity (density) evolution models are shown in the left-hand (right-hand) panel. Lines as in Fig. 1. A field of view of 1.4 sr for Swift/BAT is adopted.

We compare model predictions with the number of bright bursts detected by Swift in 3 yr of mission. Conservatively, our data sample contains only bursts with a good redshift measurement and whose peak energy was measured or well constrained by Swift itself or other satellites (such as HETE-2 or Konus-Wind). We find nine GRBs detected by Swift with $L \geq 10^{51}$ erg s$^{-1}$ in 3 yr of mission. We want to stress here that this number represents a conservative lower limit on the number of bright GRBs detected, since some luminous bursts without $z$ and/or $E_p$ can be present in the Swift catalogue. In particular, we note that a good redshift determination is obtained for $\sim 1/3$ of Swift bursts and for only a fraction of these we have a well constrained $E_p$. The cumulative distribution of the known bright bursts is shown in Fig. 2. The shaded area takes into account errors on the determination of $L$. The model results for the pure luminosity (density) evolution models are plotted in the left-hand (right-hand) panel of Fig. 2. We have also checked that our findings do not depend on the assumed $L - E_p$ correlation: considering a mean break energy (as done in SC07) for all bursts does not change significantly our results.

For the pure luminosity evolution scenario, all models here considered predict a large number of bright bursts to be detected by Swift. Indeed, they can easily account for the observed number of bursts with $L > 10^{51}$ erg s$^{-1}$. On the other hand, models in which GRB formation is confined in low-metallicity environments seems to fall short to account for the observed bright GRBs for $Z_0 > 0.1$. In particular, for $Z_0 = 0.3 Z_\odot$, as required by collapsar models (MacFadyen & Woosley 1999; Izzard, Ramirez-Ruiz & Tout 2004), only six bursts with $L \geq 10^{53}$ erg s$^{-1}$ should have been detected in 3 yr of observations.

In order to test the statistical significance of our findings, we explore the parameter space around the best-fitting parameters looking for triple ($k_{\text{GRB}}$, $\xi$, $L_0$) compatible with the sure bright burst identifications. Among these, we choose the triple that give the best agreement with the differential peak flux distribution of BATSE GRBs. Then, the null hypothesis test gives us the confidence level at which we can discard the considered model. For $Z_0 = 0.3 Z_\odot$, we find that null hypothesis is satisfied being, in the best case, the chance probability of $\sim 0.22$. However, since we are dealing with strong lower limit on the real number of bright burst detections, we have also to consider the case in which some luminous bursts are hidden among the GRBs missing redshift and/or $E_p$ measurement. We find that the null hypothesis probability decreases rapidly with the number of bright burst detections and already for 10 bright bursts it drops down to the per cent level (see Fig. 3). So, although the $Z_0 = 0.3 Z_\odot$ scenario cannot formally be discarded by available data, some degree of luminosity evolution in the GRB LF is suggested if just a few more bright bursts had to be added to our measured sample. For $Z_0 = 0.1 (0.2) Z_\odot$, the models can account up to 16 (12) bright bursts in the whole Swift data sample, i.e. just
The probability is $\xi < C = \text{data due to the possible number counts and with the number of bursts in the Swift catalogue), would imply the need of luminosity evolution required to match the number of known GRBs with $L > 10^{53} \text{erg s}^{-1}$ in 3 yr of Swift operations. Different pure density evolution models are plotted with different lines: dashed line for $Z_{th} = 0.3 Z_\odot$, dotted line for $Z_{th} = 0.2 Z_\odot$ and solid line for $Z_{th} = 0.1 Z_\odot$. The probability rapidly decreases with the number of bright bursts so that even a few more bright bursts to be added to our conservative sample would require some degree of luminosity evolution.

Figure 3. Chance probability to reproduce the differential peak flux distribution of BATSE GRBs given a model that predicts $N$ bursts with $L \geq 10^{53} \text{erg s}^{-1}$ in 3 yr of Swift operations. Different pure density evolution models are plotted with different lines: dashed line for $Z_{th} = 0.3 Z_\odot$, dotted line for $Z_{th} = 0.2 Z_\odot$ and solid line for $Z_{th} = 0.1 Z_\odot$. The probability rapidly decreases with the number of bright bursts so that even a few more bright bursts to be added to our conservative sample would require some degree of luminosity evolution.

seven (three) ‘hidden’ bright bursts (Fig. 3). For the pure evolution scenario, we find that even a relatively large population of bright bursts hidden in the Swift catalogue of bursts without good redshift and/or $E_p$ measurement, can still be accounted for.

To complete our analysis, we then consider models in which both luminosity and density evolution are present. For any value of the threshold metallicity $Z_{th}$, we derive the minimum luminosity evolution required to match the number of known GRBs with $L \geq 10^{53} \text{erg s}^{-1}$ in the 3-yr catalogue (top panel of Fig. 4). The error bars correspond to a null hypothesis probability of 1 per cent that the model reproduces the differential peak flux distribution of BATSE GRBs. We find that for $Z_{th} > 0.3 Z_\odot$, the available constraints require luminosity evolution in the GRB LF. Below this threshold, models characterized by a constant LF can account for the number of known luminous bursts considering the error bars. As already pointed out, the existence of a few bright bursts hidden among GRBs without a sure redshift and/or $E_p$ measure (more than 2/3 of the whole Swift catalogue), would imply the need of luminosity evolution even for lower value of $Z_{th}$. Moreover, note here that the existence of a distinct population of low-luminosity GRBs at low-$z$ (see e.g. Guetta & Della Valle 2007) strengthens our conclusions. In the form of the adopted LF (see equation 4), we do not include this population in our calculations. Should this population be statistically significant and present at all redshifts, the faint end of the LF would be more populated and all model predictions would be shifted towards lower values, increasing the discrepancy between model results and data. Since for pure density evolution models the LF cut-off luminosity is considerably larger than for pure luminosity evolution models, the former models would be more severely affected by the existence of a large population of underluminous bursts at any redshift. In conclusion, although we cannot rule out at a high confidence level pure density evolution models with $Z_{th} < 0.3 Z_\odot$, available data suggest some luminosity evolution in the GRB LF with redshift.

Finally, we constrain the steepness of the bright end of the GRB LF (bottom panel of Fig. 4). Very steep LF are robustly ruled out in every model considered. We find that the maximum value of the index $\xi$ is $\leq 2.6$. For the pure luminosity evolution models, we find $\xi < 2.2$. As we already pointed out, these limits could be further constrained to explain current Swift data due to the possible existence of bright bursts missed by our conservative selection and of a relatively large population of faint bursts not considered here.

4 CONCLUSION

We have computed the LF and the formation rate of long GRBs by fitting the observed differential peak flux distribution obtained by the BATSE in two different scenarios: (i) the GRB luminosity evolves with redshift and (ii) GRBs form preferentially in low-metallicity environments. In both cases, model predictions are consistent with the Swift number counts and with the number of detections at $z > 2.5$ and $> 3.5$. To discriminate between the two evolutionary scenarios, we compared the model results against the number of luminous bursts, i.e. with peak luminosity in excess of $10^{53} \text{erg s}^{-1}$, detected by Swift. Conservatively, our data sample contain only bursts with good redshift determination and measured peak energy. We find that models in which GRBs are characterized by a constant LF (i.e. for pure density evolution models) are disfavoured as they underpredict the number of luminous GRBs. Swift data can be explained assuming that the GRB luminosity evolves with redshift. Although we cannot discard pure density evolution models with $Z_{th} < 0.3 Z_\odot$ on the basis of the current sample, the existence of a few bright GRBs missed by our conservative selection criteria and/or of a relatively large population of faint GRBs would require some luminosity evolution in the GRB LF even for such low values of $Z_{th}$. On the other hand, pure luminosity evolution scenarios can account more easily for a large number of burst detections with $L > 10^{53} \text{erg s}^{-1}$. In this work, we derive lower limits to the luminosity evolution of the GRB LF with redshift for different values of the metallicity threshold for the GRB formation. Moreover, we use these constraints to set a robust upper limit on the bright end of GRB LF. We find that the number of bright GRBs detected by Swift...
implies that this cannot be very steep: $\xi \lesssim 2.2$ (pure luminosity evolution) and $\xi \lesssim 2.6$ (for $Z_{th} < 0.3 Z_\odot$).

In conclusion, we find that available Swift observations point towards a scenario where GRBs were more luminous in the past. Although the current data sample of bright GRBs with good redshift and $E_p$ determination is still very poor, our findings show that these data can be used to set important constraints on the cosmic evolution of GRBs and on the steepness of their LF.

Finally, the new constraints on the GRB LF allow us to derive robust lower limits on the number of bursts detectable by Swift at very high redshift. Assuming a trigger threshold $P_{lim} = 0.4 \text{ photon s}^{-1} \text{ cm}^{-2}$, at least $\sim$5–10 per cent of all detected GRBs should lie at $z \geq 5$, where the lower (upper) value refers to a pure luminosity evolution (pure density evolution with $Z_{th} = 0.1 Z_\odot$) model. Among these, $>1$–3 GRB yr$^{-1}$ should be detected at $z \geq 6$. These lower bounds double by lowering the Swift trigger threshold by a factor of 2 (Salvaterra et al. 2008). These results are consistent with the lower limits on the number of high-$z$ detections obtained by Salvaterra et al. (2007a, 2008) using redshift distribution constraints.

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