A COMPLETE SAMPLE OF BRIGHTSwift LONG GAMMA-RAY BURSTS. I. SAMPLE PRESENTATION, LUMINOSITY FUNCTION AND EVOLUTION

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ABSTRACT

We present a carefully selected sub-sample of Swift long gamma-ray bursts (GRBs) that is complete in redshift. The sample is constructed by considering only bursts with favorable observing conditions for ground-based follow-up searches, which are bright in the 15–150 keV Swift/BAT band, i.e., with 1-s peak photon fluxes in excess to 2.6 photons s$^{-1}$ cm$^{-2}$. The sample is composed of 58 bursts, 52 of them with redshift for a completeness level of 90%, while another two have a redshift constraint, reaching a completeness level of 95%. For only three bursts we have no constraint on the redshift. The high level of redshift completeness allows us for the first time to constrain the GRB luminosity function and its evolution with cosmic times in an unbiased way. We find that strong evolution in luminosity ($\delta \beta = 2.3 \pm 0.6$) or in density ($\delta \rho = 1.7 \pm 0.5$) is required in order to account for the observations. The derived redshift distributions in the two scenarios are consistent with each other, in spite of their different intrinsic redshift distributions. This calls for other indicators to distinguish among different evolution models. Complete samples are at the base of any population studies. In future works we will use this unique sample of Swift bright GRBs to study the properties of the population of long GRBs.

Key words: gamma-ray burst: general – stars: formation – cosmology: observations

Online-only material: color figures

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. They are detected at all redshifts, from the local universe up to the extreme high redshifts (Salvaterra et al. 2009a; Tanvir et al. 2009; Cucchiara et al. 2011b). Our knowledge of the distribution of long GRBs through cosmic times is still hampered by the fact that most of the observed Swift GRBs are without redshift. Indeed, the measure of the burst light curves and the environment in which they explode.

To this end, we present in this paper a well-selected, complete sub-sample of the full Swift database. We select bursts that have favorable observing conditions for redshift determination from the ground and that are bright in the 15–150 keV Swift/BAT band. We find 58 bursts matching our selection criteria with a completeness level in redshift determination of 90%. The completeness level increases to $\sim$95% by considering the redshift constraints imposed by the detection of the afterglow or host galaxy in some optical filters. Therefore, our selection criteria allow us to construct a sizable sample of long bursts that is (almost) complete in redshift, providing a solid basis for the study of the long-GRB population in an unbiased way. In particular, since our selection is based on the brightness in the Swift/BAT band, our sample is not biased against the detection of dark bursts; thus, it provides a complete description of the whole long-GRB population.

In the present paper, we will take advantage of the high completeness level of our sample to constrain the GRB luminosity function (LF) and its evolution with cosmic time. In the past few years, this problem has been faced by many different authors (e.g., Porciani & Madau 2001; Firmani et al. 2004; Guetta et al. 2005; Natarajan et al. 2005; Daigne et al. 2006; Salvaterra & Chincarini 2007; Salvaterra et al. 2009b; Butler et al. 2010; Wanderman & Piran 2010; Campisi et al. 2010; Qin et al. 2010; Virgili et al. 2011; Robertson & Ellis 2012). There is general agreement about the fact that GRBs must have experienced some sort of evolution through cosmic time, whereas the nature and the level of such evolution are still matter of debate. Most of the previous works relied on the assumption that bursts lacking redshift measurements closely follow the redshift distribution of bursts with known $z$. In the past, we tried to overcome this assumption by deriving a conservative lower limit for the level of evolution of the burst's luminosity. In future works we will use this sample to study the correlation between physical parameters of the bursts and the properties of the burst light curves and the environment in which they explode.

This paper is organized as follows: In Section 2, we describe our selection criteria and present our sample. We present our models of the GRB LF and redshift distribution in Section 3, while the results are presented in Section 4. We extrapolate our findings to the detection limit of Swift in Section 5. Finally, in Section 6 we draw our conclusions.
2. THE SAMPLE

The redshifts of about 1/3 of all GRBs observed by the Swift satellite (Gehrels et al. 2004) have been measured. While this represents an enormous improvement with respect to the pre-Swift situation, the sample is still far from being considered complete. Jakobsson et al. (2006) proposed a series of criteria in order to carefully select long GRBs which have observing conditions favorable for redshift determination. In particular, they required that: (1) the burst has been well localized by Swift/XRT and its coordinate has been quickly distributed, (2) the Galactic extinction in the burst direction is low ($A_V < 0.5$), (3) the GRB declination is $-70° < \delta < 70°$, (4) the Sun-to-field distance is $\theta_{Sun} > 55°$, and (5) no nearby bright stars are present. While none of the above criteria are expected to significantly alter the redshift distribution of observed GRBs, the completeness level is increased to $\sim 53%$. Still, this level of completeness is far too low to permit robust population studies.

In order to construct a more complete sample, we restrict ourselves to GRBs that are relatively bright in the 15–150 keV Swift/BAT band. In particular, we select bursts matching the above criteria and having 1-s peak photon flux $P > 2.6$ photons $s^{-1} cm^{-2}$. This corresponds to an instrument that is $\sim 6$ times less sensitive than Swift. Fifty-eight GRBs match our selection criteria; these are listed in Table 1 up to 2011 May. Fifty-two of them have measured redshift so that our completeness level is 90%. Of these 52, all but two (namely, GRB 070521, Perley et al. 2009; and GRB 080602, Rossi et al. 2012) have spectroscopic confirmed redshift either from absorption lines or from emission lines of the GRB host galaxy. Moreover, for three of the six bursts lacking measured $z$, the afterglow or the host galaxy have been detected in at least one optical filter, so that $\sim 95%$ of the bursts in our sample have a constrained redshift. We note that, while our sample represents only $\sim 10%$ of the full Swift sample, it contains more than 30% of the long GRBs with known redshift.

The redshift distribution of the bursts in our sample is shown in Figure 1. In spite of the rather severe cut in the observed photon flux, the bursts in our sample have a broad distribution in redshift. The mean (median) redshift of the sample is 1.84 (1.64 ± 0.10) with a long tail at high-$z$ extending, at least, up to $z = 5.47$. 

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Table 1

| GRB   | Redshift | Ref. | GRB   | Redshift | Ref. | GRB   | Redshift | Ref. | GRB   | Redshift | Ref. |
|-------|----------|------|-------|----------|------|-------|----------|------|-------|----------|------|
| 050318 | 1.44 | 1 | 060107 | 1.26 | 2 | 080603B | 2.69 | 2 | 090709A | <3.5 | 15 |
| 050401 | 2.90 | 2 | 061021 | 0.35 | 2 | 080605 | 1.64 | 2 | 090715B | 3.00 | 16 |
| 050416A | 0.65 | 3 | 061121 | 1.31 | 2 | 080607 | 3.04 | 2 | 090812 | 2.45 | 17 |
| 050525A | 0.64 | 4 | 061222A | 2.09 | 3 | 080613B | ... | ... | 090926B | 1.24 | 18 |
| 050802 | 1.71 | 2 | 070306 | 1.50 | 2 | 080721 | 2.59 | 2 | 091018 | 0.97 | 19 |
| 050922C | 2.20 | 2 | 070328 | <4 | 2 | 080804 | 2.20 | 2 | 091020 | 1.71 | 20 |
| 060206 | 4.05 | 2 | 070521 | 1.35 | 3 | 080916A | 0.69 | 2 | 091127 | 0.49 | 21 |
| 060210 | 3.91 | 2 | 071020 | 2.15 | 2 | 081007 | 0.53 | 8 | 091208B | 1.06 | 22 |
| 060306 | 3.5 | 5 | 071112C | 0.82 | 2 | 081121 | 2.51 | 9 | 100615A | ... | ... |
| 060614 | 0.13 | 2 | 071117 | 1.33 | 2 | 081203A | 2.10 | 10 | 100621A | 0.54 | 23 |
| 060814 | 1.92 | 2 | 080319B | 0.94 | 2 | 081221 | 2.26 | 24 | 100728B | 2.106 | 24 |
| 060904A | ... | ... | 080319C | 1.95 | 2 | 081222 | 2.77 | 11 | 110205A | 2.22 | 25 |
| 060908 | 1.88 | 2 | 080413B | 1.1 | 2 | 090102 | 1.55 | 12 | 110503A | 1.613 | 26,27 |
| 060912A | 0.94 | 5 | 080430 | 0.77 | 6 | 090201 | <4 | 13 |  |
| 060927 | 5.47 | 2 | 080602 | ~1.4 | 7 | 090424 | 0.54 | 14 |  |

Notes.

1 Based on the R-band host galaxy detection in ESO-VLT/FORS2 imaging data obtained with the program 177.A-0591 (PI: J. Hjorth), taken from the ESO Archive.

2 Based on VLT/X-shooter spectra of the host galaxies obtained with the program 087.A-0451 (PI: H. Flores). The spectra were reduced using the X-shooter data reduction pipeline version 1.3.7 (see Goldoni et al. 2006). Thanks to the identification procedures using the ESO-MIDAS package. At the afterglow position we could identify an object, showing a continuum signature in the spectra, which we therefore consider to be the host galaxy of GRB 060814. We can also identify the galaxy reported by Thoene et al. (2007), at $z = 0.84$, but this object is offset from the afterglow position. VLT/X-shooter spectroscopy of the host galaxy has been performed within the program 084.A-0303 (PI: J. Fynbo). We reduced these spectra using the X-shooter data reduction pipeline version 1.2.0 (see Goldoni et al. 2006). Thanks to the identification in the NIR arm of the [O ii] doublet, [O iii] λλ3726,3729, and Hα emission lines associated with the host galaxy, we can establish a redshift of $z = 1.92$ for GRB 060814.

3 Photometric redshift on the bases of the most probable host galaxy association in the XRT error circle (Rossi et al. 2012).

4 Redshifts or limits are provided in the following references: (1) Berger et al. 2005; (2) Fynbo et al. 2009a and references therein; (3) Perley et al. 2009; (4) Foley et al. 2005; (5) Levan et al. 2007; (6) Cucchiara & Fox 2008; (7) Rossi et al. 2012; (8) Berger et al. 2008; (9) Berger & Rauch 2008; (10) Kain et al. 2009; (11) Cucchiara et al. 2008; (12) de Ugarte Postigo et al. 2009b; (13) D’Avanzo et al. 2009; (14) Chornock et al. 2009; (15) D. A. Perley et al. 2012, in preparation; (16) Wiersma et al. 2009a; (17) de Ugarte Postigo et al. 2009a; (18) Fynbo et al. 2009b; (19) Chen et al. 2009; (20) Xu et al. 2009; (21) Cucchiara et al. 2009; (22) Wiersma et al. 2009b; (23) Milvang-Jensen et al. 2010; (24) Flores et al. 2010; (25) Cucchiara et al. 2011a; (26) de Ugarte Postigo et al. 2011; (27) D’Avanzo et al. 2011.

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6 Up to 2011 May, the sample consists of 248 long GRBs, 132 with measured redshift. See http://www.raunvis.hi.is/~pjra/GRBsample.html
The expected redshift distribution of GRBs can be computed once the GRB LF and the GRB formation history have been specified. We briefly recap here the adopted formalism and refer the interested reader to Salvaterra & Chincarini (2007) and Salvaterra et al. (2009b) for model details.

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

\[
P = \frac{(1 + z)^{\phi(1+z)E_{\text{max}}}}{4\pi d_L^2(z)} S(E)\,dE, \tag{1}
\]

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 a Band function with low- and high-energy spectral indices \(-1\) and \(-2.25\), respectively (Band et al. 1993; Preece et al. 2000; Kaneko et al. 2006). The spectrum normalization is imposed by ensuring that the isotropic-equivalent peak luminosity is \( L = \int_{15\text{keV}}^{150\text{keV}} E S(E)\,dE \). In order to broadly estimate the peak energy of the spectrum, \( E_p \), for a given \( L \), we assume the validity of the correlation between \( E_p \) and \( L \) (Yonetoku et al. 2004; Ghirlanda et al. 2005; Nava et al. 2011).

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

\[
\frac{dN}{dt}(P_1 < P < P_2) = \int_0^\infty \frac{dV(z)}{dz} \frac{\Delta\Omega_i}{4\pi} \frac{\Psi_{\text{GRB}}(z)}{1 + z} \frac{L^2}{P_1} \int_{P_1(z)}^{P_2(z)} dL' \phi(L'), \tag{2}
\]

where \( dV(z)/dz = 4\pi cd_L^2(z)/[H(z)(1 + z)^2] \) is the comoving volume element, \( H(z) = H_0[\Omega_M(1 + z)^3 + \Omega_\Lambda + (1 - \Omega_M - \Omega_\Lambda)(1 + z)^2]^{1/2} \), \( \Delta\Omega_i \) is the solid angle covered on the sky by the survey, and the factor \((1 + z)^{-2}\) accounts for cosmological time dilation. Finally, \( \Psi_{\text{GRB}}(z) \) is the comoving burst formation rate.

We explore two general expressions for the GRB LF; a single power law with an exponential cutoff at low luminosity (exponential LF) and a broken power-law LF. The former is described by

\[
\phi(L) \propto \left(\frac{L}{L_{\text{cut}}}ight)^{-\xi_b} \exp\left(-\frac{L_{\text{cut}}}{L}\right), \tag{3}
\]

and the latter by

\[
\phi(L) \propto \begin{cases} 
\left(\frac{L}{L_{\text{cut}}}ight)^{-\xi_b} & \text{for } L \leq L_{\text{cut}} \\
\left(\frac{L}{L_{\text{cut}}}ight)^{-\xi_f} & \text{for } L > L_{\text{cut}}.
\end{cases} \tag{4}
\]

where \( L_{\text{cut}} \) is the cutoff (break) luminosity, and \( \xi_b \) and \( \xi_f \) are the bright- and faint-end power-law indices, respectively. The GRB LF is normalized to unity. In order to prevent the integral from diverging, we adopt a minimum GRB luminosity \( L_{\text{min}} = 10^{48} \text{ erg s}^{-1} \). We find that our results do not change if a minimum luminosity of \( 10^{48} \text{ erg s}^{-1} \) is adopted (apart from the value of the normalization \( \eta_0 \)).

### 3. MODEL DESCRIPTION

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\]

where \( dV(z)/dz = 4\pi cd_L^2(z)/[H(z)(1 + z)^2] \) is the comoving volume element, \( H(z) = H_0[\Omega_M(1 + z)^3 + \Omega_\Lambda + (1 - \Omega_M - \Omega_\Lambda)(1 + z)^2]^{1/2} \), \( \Delta\Omega_i \) is the solid angle covered on the sky by the survey, and the factor \((1 + z)^{-2}\) accounts for cosmological time dilation. Finally, \( \Psi_{\text{GRB}}(z) \) is the comoving burst formation rate.

We explore two general expressions for the GRB LF; a single power law with an exponential cutoff at low luminosity (exponential LF) and a broken power-law LF. The former is described by

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\end{cases} \tag{4}
\]

where \( L_{\text{cut}} \) is the cutoff (break) luminosity, and \( \xi_b \) and \( \xi_f \) are the bright- and faint-end power-law indices, respectively. The GRB LF is normalized to unity. In order to prevent the integral from diverging, we adopt a minimum GRB luminosity \( L_{\text{min}} = 10^{48} \text{ erg s}^{-1} \). We find that our results do not change if a minimum luminosity of \( 10^{48} \text{ erg s}^{-1} \) is adopted (apart from the value of the normalization \( \eta_0 \)).

### 4. MODEL RESULTS

We optimize the value of the model free parameters including the GRB LF, the normalization \( \eta_0 \), and the evolution parameter, by minimizing the \( C \)-stat function (Cash 1979) jointly fitting the observed differential number counts in the 50–300 keV band of BATSE (Stern et al. 2001, 2002) and the observed redshift distribution of bursts in our sample with photon fluxes in excess of 2.6 photons s\(^{-1}\) cm\(^{-2}\) in the Swift 15–150 keV band. For BATSE, we adopt 9.1 yr of observation with an average exposure factor of 0.47, including both Earth-blocking and average duty cycle for a useful 1.024 s continuous record (Stern et al. 2002). While our complete Swift sample provides a powerful test for the existence and the level of evolution of the long-GRB population with redshift, the fit to the BATSE number counts allows us to obtain the present-day GRB rate density and to better constrain the GRB LF free parameters. It is worth noting that the best-fit parameters also provide a good fit of the Swift differential peak-flux number counts once the 15–150 keV band, the field of view of 1.4 sr, and the observing lifetime of Swift are considered (see also Salvaterra & Chincarini 2007). The best-fit parameter values together with their \( 1\sigma \) confidence level\(^9\) for different models are provided in Table 2. The corresponding redshift distributions for bursts with \( P > 2.6 \) photons s\(^{-1}\) cm\(^{-2}\) are shown in Figure 1. We test for each model the two different GRB LF parameterizations described in the previous section, and we report in Figure 1 the one that gives the best result.

\(^7\) We adopt the “concordance” model values for the cosmological parameters: \( h = 0.7, \Omega_M = 0.3, \) and \( \Omega_\Lambda = 0.7 \).

\(^8\) For those GRBs lacking redshift measurement, we randomly assign a redshift from a flat \( z \)-distribution (taking into account the available redshift constraints) to avoid introducing any a priori bias. We produce 1000 of such random realizations.

\(^9\) The errors at the \( 1\sigma \) confidence level of the parameters of interest (GRB LF and evolution parameter) adopting a C-stat increment of 2.30, 3.53, and 4.72 for 2, 3, and 4 parameters of interest, respectively.
In the first simple (no-evolution) scenario, we can assume that long GRBs trace the cosmic star formation and that their LF is constant in redshift \( L_{\text{cut}}(z) = L_{\text{cut,0}} \). In this case the cosmic GRB formation rate is \( \Psi_{\text{GRB}}(z) = \eta_0 \Psi_*(z) \), where \( \Psi_*(z) \) is the normalized cosmic star formation rate (SFR) and \( \eta_0 \) is the present-day GRB formation rate density in units of Gpc\(^{-3}\) yr\(^{-1}\).

We adopt the cosmic SFR recently computed by Li (2008), which extended the previous work by Hopkins & Beacom (2006) to higher redshifts.

This no-evolution scenario (dashed line in Figure 1) clearly does not provide a good representation of the observed redshift distribution of our sample, confirming previous findings (e.g., Daigne et al. 2006; Salvaterra & Chincarini 2007; Salvaterra et al. 2009b; Qin et al. 2010; Wanderman & Piran 2010; Virgili et al. 2011). In particular, the peak of the GRB redshift distribution is at a lower redshift than observed; consequently, the rate of GRBs at high-z is underestimated. This is confirmed by a more detailed statistical analysis. Indeed, on the basis of the Akaike information criterion (Akaike 1974) we can safely discard this model as being \( \sim 10^{-14} \) times as probable as the luminosity evolution model to minimize the information loss (the density evolution model with the broken power-law LF is 0.24 times as probable as the luminosity one with the cutoff LF). Moreover, a Kolmogorov–Smirnov (K-S) test between the no-evolution best-fit model and the data in our sample gives a chance probability of \( \sim 5 \times 10^{-5} \) that the two distributions are drawn from the same parent population.

In the following sections, we will consider evolution scenarios that may enhance the number of detections at high-z. In particular, we explore (1) a luminosity evolution model in which high-z GRBs are typically brighter than low-z bursts, and (2) two density evolution models, both leading to an enhancement of the GRB formation rate with redshift. Hybrid models, with both luminosity and density evolution, are possible in principle. However, the fit with hybrid models is degenerate and does not provide useful constraints. Therefore, we prefer here to consider the two scenarios separately to highlight possible similarities and differences between the two kinds of evolutions.

### 4.1. No-Evolution Model

Evolution in the GRB LF can provide an enhancement of the high-z GRB detection, representing a viable way to reconcile model results with the observations. Here, we consider the possibility that the cutoff (break) luminosity is an increasing function of the redshift, that is \( L_{\text{cut}}(z) = L_{\text{cut,0}}(1 + z)^{\delta_l} \). We find that a strong luminosity evolution with \( \delta_l = 2.3 \pm 0.6 \) is required to reproduce the observed redshift distribution of the bursts in our complete sample (light shaded area in Figure 1). The result does not depend on the assumed expression of the GRB LF.

### 4.2. Luminosity Evolution Model

An increase in the rate of GRB formation with redshift (on the top of the known evolution of the SFR density) will also lead to enhanced detection of bursts at high-z. As a general case, we parameterize the evolution in the GRB formation rate as \( \eta(z) = \eta_0 (1 + z)^{\delta_l} \). By fitting our data sets, we find that strong density evolution is required with \( \delta_l = 1.7 \pm 0.5 \). The amount of evolution does not depend on the assumed expression of the GRB LF. However, we note that the cutoff LF tends to underestimate the number of low-z bursts with respect to the observed one, leading to some discrepancy with the first data point.

The large value of \( \delta_l \) implies an important shift in the peak of the GRB formation rate toward higher redshifts with respect to stars. We further investigate this issue by applying a “correction” to the shape of the cosmic SFR. This is usually parameterized as three power laws (Hopkins & Beacom 2006; Li 2008) with power index \( \alpha_1 = 3.3, \alpha_2 = 0.055, \) and \( \alpha_3 = -4.46 \), and breaks at \( z_1 = 0.993 \) and \( z_2 = 3.8 \) (Li 2008). We fit our data sets by leaving one of the above parameters free to vary in addition to those describing the GRB LF. We find that the observed redshift distribution of bursts in our sample can be explained either by an increase in the redshift of the first break to \( z_1 = 2.5 \pm 0.5 \) or by a hardening of the second power law to \( \alpha_2 = 2.4 \pm 0.4 \). In both cases, the GRB formation rate is found to peak at a much higher redshift with respect to stars. The intrinsic redshift distribution of GRBs is shown in Figure 2.

### 4.3. Density Evolution Models

#### Table 2

| Model         | Evolution Parameter | \( \eta_0 \) | \( L_{\text{cut,0}} \) | \( \xi_f \) | \( \xi_s \) | C-stat | AIC |
|---------------|---------------------|-------------|----------------|-----------|-----------|--------|-----|
| No evolution  | ...                 | 0.30        | 1.0^{+0.9} \_0.5 | ...       | 2.0^{+0.16} \_0.12 | 93     | 99  |
| Luminosity    | \( \delta_l = 2.3 \pm 0.6 \) | 0.14        | 0.22^{+0.27} \_0.13 | ...       | 2.0^{+0.13} \_0.10 | 27     | 35  |
| Density       | \( \delta_l = 1.6 \pm 0.4 \) | 0.03        | 3.07^{+3.09} \_1.36 | ...       | 2.0^{+0.23} \_0.17 | 38     | 46  |
| Metal         | \( Z_{\text{th}} = 0.14 \pm 0.16 \) | 0.04        | 4.4^{+5.6} \_2.8  | ...       | 2.1^{+0.30} \_0.20 | 37     | 45  |

| Model         | Evolution Parameter | \( \eta_0 \) | \( L_{\text{cut,0}} \) | \( \xi_f \) | \( \xi_s \) | C-stat | AIC |
|---------------|---------------------|-------------|----------------|-----------|-----------|--------|-----|
| No evolution  | ...                 | 2.06        | 2.6^{+0.06} \_0.21 | 1.56^{+1.11} \_0.35 | 2.3^{+0.35} \_0.50 | 88     | 96  |
| Luminosity    | \( \delta_l = 2.1 \pm 0.6 \) | 0.21        | 0.55^{+0.06} \_0.34 | 0.74^{+1.42} \_1.36 | 1.9^{+0.14} \_0.32 | 33     | 43  |
| Density       | \( \delta_l = 1.7 \pm 0.5 \) | 0.24        | 3.8^{+0.63} \_0.27 | 1.50^{+1.6} \_0.32 | 2.3^{+0.32} \_0.32 | 27     | 37  |
| Metal         | \( Z_{\text{th}} = 0.10 \pm 0.18 \) | 0.41        | 4.7^{+0.75} \_0.35 | 1.4^{+0.17} \_0.35 | 2.5^{+0.60} \_0.50 | 26     | 36  |

Notes. Errors show the 1σ confidence level for the parameters of interest (see the text in Section 4 for details). The last two columns report the total C-stat value (i.e., the sum of the C-stat values obtained from the fit of the BATSE and the Swift data set) and the Akaike information criterion (AIC) score, respectively. We note that in order to properly compare different models the AIC criterion must be considered, where exp(AIC_{\text{min}} - AIC) is the relative probability that the ith model minimizes the (estimated) information loss with respect to the model with the minimum AIC, AIC_{\text{min}}. The total number of data points in the fit is 33. The GRB formation rate at \( z = 0 \) is given in units of Gpc\(^{-3}\) yr\(^{-1}\) and the characteristic luminosity \( L_{\text{cut,0}} \) in units of 10\(^{51}\) erg s\(^{-1}\).
Dotted (dashed) lines indicate the modified SFR with $z$ the density evolution model and for the metallicity threshold model, respectively. In all cases, no evolution of the GRB LF has been assumed.

**A subclass of density evolution models foresees the formation of long GRBs preferentially in low-metallicity environments. In this case, GRBs will be biased tracers of the star formation activity, being that their formation is suppressed at low-$z$ where most of the galaxies are relatively metal-rich.** Following Langer & Norman (2006), we model the fractional mass density belonging to metallicity below a given threshold, $Z_{th}$, as

$$\Sigma(z) = \frac{\Gamma(0.84, (Z_{th}/Z_\odot)^{2}10^{0.3z})}{\Gamma(0.84)},$$

where $\Gamma$ ($\Gamma^*$) are the incomplete (complete) gamma function, and $\Gamma(0.84) \simeq 1.122$. The GRB formation rate is then given by $\Psi_{GRB}(z) \propto \Sigma(z)^{\alpha_z}(z)$.

We fit our data sets, leaving $Z_{th}$ free to vary. The available data are well described by models with $Z_{th} \lesssim 0.3 Z_\odot$, almost independently of the assumed LF. The resulting LF is similar to the one obtained for the density evolution model. Indeed, the two predicted redshift distributions match each other within the uncertainties, and we refer to the dark shaded curves in Figure 1 for the metallicity threshold model.

The range of values for $Z_{th}$ found in our analysis is in agreement with the expectation of the collapsar model (Woosley & Heger 2006; Fryer et al. 1999). However, such strong metallicity cutoffs seem to be inconsistent with the observed properties of the GRB host at $z < 1$ (Mannucci et al. 2011; Kocevski & West 2011; Campisi et al. 2011b). In particular, Campisi et al. (2011b) have shown that in the presence of a strong metallicity cutoff for the GRB progenitor star, the expected distribution of GRB host galaxies in the $M-Z$ and Fundamental Metallicity Relation planes is much flatter than observed. Larger metallicity thresholds will require some luminosity evolution in order to reproduce the available data. For $Z_{th} = 0.5 Z_\odot$, the typical burst luminosity should increase with redshift as $(1 + z)^{1.3 \pm 0.6}$.

**5. SWIFT REDSHIFT DISTRIBUTION**

We compute the redshift distribution expected for the full Swift data set, assuming a photon flux limit of $P = 0.4$ photons s$^{-1}$ cm$^{-2}$ and fixing the model free parameters to the values given in Table 2. The results are shown in Figure 3 for the different evolution scenarios explored here. The models are compared with the redshift distribution inferred from the sample of GRBs observed by GROND (Greiner et al. 2011). This sample has a completeness level similar to ours but is smaller in size and covers a broader redshift range. We find that our evolution models provide a good description of the observed redshift distribution of the GROND sample without the need for any adjustment of the free parameters (a K-S test gives a probability of 50%), whereas the no-evolution model is excluded (probability of $5 \times 10^{-4}$). This further confirms the reliability of our analysis, strengthening our conclusions.

The predicted redshift distribution of bursts detectable by Swift presents a steep rise at low-$z$, peaking at $z \sim 2$ with a tail extending at higher redshifts. The median redshift of the distribution is $z = 2.05 \pm 0.15$, where the error takes into account the uncertainties in the evolution parameters. We predict that 3%–5% of the bursts lie at $z > 5$, which is consistent with the observational estimate of $5.5% \pm 2.8$% (Greiner et al. 2011). This further confirms that the majority of dark GRBs are not high-$z$ sources but are more likely obscured by dust (Perley et al. 2009; Greiner et al. 2011). At $z > 8$, we expect 1.3–3.5
GRBs\textsuperscript{10} among the 530 Swift GRBs. This is consistent with the two detections reported so far, i.e., GRB 090423 at \( z = 8.2 \) (Salvaterra et al. 2009a; Tanvir et al. 2009) and GRB 090429B at \( z \sim 9.4 \) (Cucchiara et al. 2011b).

It is worth noting that the two evolution scenarios explored here predict very similar distributions. Therefore, we cannot distinguish between luminosity and density evolution simply on the basis of the Swift observed redshift distribution.

6. CONCLUSIONS

We select a sub-sample of Swift long GRBs that is complete in redshift. The sample is composed of bursts with favorable observing conditions and with 1-s peak photon fluxes \( P \geq 2 \) photons s\(^{-1}\) cm\(^{-2}\). It contains 58 bursts with a completeness level of \( \sim 90\% \) and provides the basis for unbiased statistical studies of the properties of long GRBs and their evolution with redshift. GRBs can be used to study fundamental issues in astronomy and astrophysics, such as the SFR and stellar and metal abundances evolution. They can be used as tracers of galaxy evolution, of ISM composition, and to investigate the early universe. Complete and fully representative samples of GRBs are therefore unique tools for performing these investigations.

Here, we use the observed burst redshift distribution of our complete sample to probe and constrain the evolution of the long-GRB population in redshift. We confirm that GRBs must have experienced some sort of evolution to become more luminous or more numerous in the past than observed today. We find that in order to match the observed distribution, the typical burst luminosity should increase to \((1+z)^{1.7\pm0.3}\) or the GRB rate density to \((1+z)^{2.3\pm0.6}\) on top of the known cosmic evolution of the SFR. This result does not depend on the assumed expression of the GRB LF. We also explore models in which GRBs form preferentially in low-metallicity environments. We find that the metallicity threshold for GRB formation should be lower than some sort of evolution to become more luminous or more numerous in the past than observed today. We find that in order to match the observed distribution, the typical burst luminosity should increase to \((1+z)^{2.3\pm0.6}\) or the GRB rate density to \((1+z)^{1.7\pm0.3}\) on top of the known cosmic evolution of the SFR. This result does not depend on the assumed expression of the GRB LF. We also explore models in which GRBs form preferentially in low-metallicity environments. We find that the metallicity threshold for GRB formation should be lower than

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\textsuperscript{10} We do not consider here the possible contribution of Pop III GRBs that may provide additional GRBs at very high-z (Campisi et al. 2011a; de Souza et al. 2011).
