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# The Luminosity Function and Formation Rate History of GRBs(*)

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**Summary.** — The isotropic Luminosity Function (LF) and Formation Rate History (FRH) of long GRBs is by the first time constrained by using *jointly* both the observed GRB peak-flux and redshift distributions. Our results support an evolving LF and a FRH that keeps increasing after $z = 2$. We discuss some interesting implications related to these results.

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## 1. – Introduction

The primordial and most extensive information on GRBs obtained directly from observations is the differential peak-flux, $P$, distribution, the so commonly called $\log N$-$\log P$ diagram (NPD). The NPD is the convolution of basically three factors: the intrinsic LF, the FRH and the cosmic volume. In the past, several attempts were done to constrain the LF from fits to the NPD, assuming arbitrary GRB FRHs and cosmologies. The results were rather poor because the complicated mixing between the model LF and FRH introduces a high degeneracy among these factors in the NPD. The most direct way to infer both the LF and the FRH is based on the observational luminosity-redshift diagram [1-3]. Unfortunately, this strategy is so far limited by the small number of GRBs with known or inferred $z$, by the bias introduced by the given method to infer $z$, and by the sensitivity limit related to the $z$ estimate. We propose [4] a new strategy for constraining the GRB LF and FRH based on the joint use of the NPD and the observed or inferred GRB differential $z$ distribution (the $N$-$z$ diagram, NZD).

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## 2. – The method and the data

The differential NPD and NZD are modelled by seeding at each $z$ a large number of GRBs with a given rate, $\dot{\rho}_{\rm GRB}$, and LF, $f(\mathrm{L}_{\rm iso})\mathrm{dL}_{\rm iso}$, and then by propagating the flux of each source to $z = 0$. We use the popular ΛCDM cosmology with $\Omega_m$=0.29, $\Omega_\Lambda = h = 0.71$. Here $\mathrm{L}_{\rm iso}$ in the rest frame is defined as $\mathrm{L}_{\rm iso}=\int_{30\rm keV}^{10000\rm keV} ES(E)\mathrm{d}E$, where $S(E)$ is the Band [5] energy spectrum with the (average) parameters taken from [6]. The break energy at rest, $E_b$, is assumed either constant (512 keV [7]) or dependent on $\mathrm{L}_{\rm iso}$ [3] ($E_b = 15$ $(\mathrm{L}_{\rm iso}/10^{50}$ erg s$^{-1})^{0.5}$ keV). The sensitivity band at $z = 0$ is fixed to the 50–300 keV range of BATSE.

We explore two models for the LF, the single and double power laws (SPL and DPL, respectively), and two cases, one with a non-evolving LF, and another one where $\mathrm{L}_{\rm iso}$ scales with $z$ as $(1 + z)^\delta$ [2, 3]. For $\dot{\rho}_{\rm GRB}$, we adopt the bi-parametric star formation rate (SFR) function, $\dot{\rho}_{\rm SF}(z; a, b)$, given in [7] multiplied by a normalisation factor $K$, and by a function $\eta(z; c)$ that allows to control, through its parameter $c$, the growth or decline of $\dot{\rho}_{\rm GRB}$ at $z > 2$. The strategy is to constrain seven parameters (3 of LF, 3 of FRH and $\delta$, for details see [4]) by applying a *joint* fit of the model predictions to the observed NPD and NZD (including their errors). The fitting is based on an extension of the Levenberg-Marquardt method to find the least total $\chi^2 = \chi^2_{\rm NP} + \chi^2_{\rm NZ}$.

We use the widest sample to date for the NPD [8]. It consists of a collection of i) 3255 BATSE GRBs longer than 1 s, and with a $P$ limit appropriately extended down to 0.1 photons cm$^{-2}$ s$^{-1}$, and ii) a sample of bright *Ulysses* GRBs with $P$ up to $\sim 300$ photons cm$^{-2}$ s$^{-1}$. For the NZD, we use two samples. One consists of a set of 220 BATSE GRBs with $z'$s inferred by using the luminosity-variability empirical relation [9], and the other comprises 33 GRBs with known $z$. The latter is corrected for several selection effects.

## 3. – Results and discussion

We have run several combinations of models, with an SPL or DPL LF, adopting an $E_b$ constant or dependent on $\mathrm{L}_{\rm iso}$, and either without evolution ($\delta = 0$) or including $\delta$ among the parameters to optimise. The obtained LFs and FRHs are shown in fig. 1 (curves) together to the observational data (error bars). A detailed analysis of the fittings of these different models to the NPD and NZD data is presented in [4]. In the following, we highlight some of the results from this analysis:

*GRB LF and jet angle distribution.* As seen in fig. 1 models with non-evolving LFs (SPL or DPL, dotted curves) give in general poor fits to the NPD and NZD. The best joint fits are obtained for models with evolving LFs ($\propto (1+z)^\delta$, solid lines). The optimal values we find for $\delta$ are $1.0 \pm 0.2$. Note that the increasing of $\mathrm{L}_{\rm iso}$ with $z$ increases the probability to observe GRBs from very high $z'$s. The fits are slightly better for the (evolving) SPL LFs than for the DPL ones. The best range of slopes of the SPL LF is $\gamma = 1.57 \pm 0.03$ ($f(\mathrm{L}_{\rm iso})\mathrm{dL}_{\rm iso} \propto \mathrm{L}_{\rm iso}{}^{-\gamma}$). If the LF is related to collimation effects, we have compared our results with the *universal structured jet* and with the *quasi-universal Gaussian structured jet* models [4]. Our results imply an intermediate case between the universal structured jet model with $\epsilon(\theta) \propto \theta^{-2}$ and the quasi-universal Gaussian structured jet model. For the uniform jet model, the jet angle distribution covers an indicative range between 2° and 15° at $z = 1$. These results correspond to the case of a luminosity-depending $E_b$ in the model LFs, but we find that for $E_b$ = const the differences are not significant.

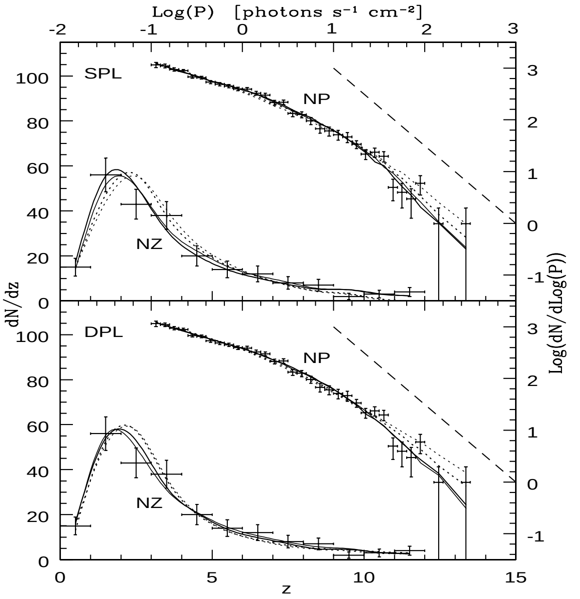

Fig. 1. – Top panel: Peak flux differential distribution (NP) with the axis in the top-right part, and $z$ differential distribution (NZ) with the axis in the bottom-left part, both for a SPL LF. Error bars show the NP data from [8] and the NZ data according to [9], respectively. Dotted lines are for models without evolution, while solid lines are for models with the evolution parameter $\delta$ optimised. Thin and thick lines identify the cases with $E_{\rm b} = 511\,{\rm keV}$ or $E_{\rm b}$ depending on $L_{\rm iso}$, respectively. Dashed straight line is the $-3/2$ uniform distribution (Euclidean) behaviour in the NPD. Bottom panel: Same as in top panel but for a DPL LF.

*GRB FRH and the connection with the cosmic SFR.* The models that best fit the observed NPD and NZD imply not only an evolving LF but also FRHs, $\dot\rho_{\rm GRB}(z)$, which steeply increase (by a factor of $\sim 30$) from $z = 0$ to $z \approx 2$ and then continue increasing gently up to $z \sim 10$ as $(1+z)^{1.4}$ and $(1+z)$ for the SPL and DPL LFs, respectively. This behaviour of the GRB FRH is qualitatively similar to the one of the cosmic SFRH. Figure 2 shows a comparison of the cosmic SFRH traced by rest-frame UV luminosity (corrected by dust obscuration) with the GRB FRH translated to SFRH under the assumption of a non evolving Initial Mass Function (IMF). The shaded area corresponds to the range of GRB models (including the uncertainties) with evolving ($\delta = 1$) SPL and DPL LFs that best fit the NPD and NZD data.

From $z = 2-3$ to $z = 6$, the cosmic SFRH traced by UV luminosity decreases slightly [10] or strongly [11], while the SFRH linked to GRBs keeps increasing. This difference, if proved in future studies, could be related to two effects. i) A significant contribution to the cosmic SFRH at $z > 2$ seems to come from sources emitting strongly in the rest-frame far infrared/submillimetre (not seen in UV). GRBs could be also tracers of the dust-enshrouded SFRH of these galaxies (*e.g.*, [12]). ii) The IMF in low-metallicity gas (high $z'$s) could be biased toward higher masses compared to the present-day IMF, favouring in this way an increasing GRB formation rate with z. From $z = 1-2$ to $z = 0$ the UV-luminosity SFRH decreases by less than an order of magnitude, while the SFRH linked to GRBs decreases roughly by a factor of 30. Due to the uncertainty on the $z$ determination any definitive conclusion about this difference has to be supported by a more extended sample with know $z$ for NZD.

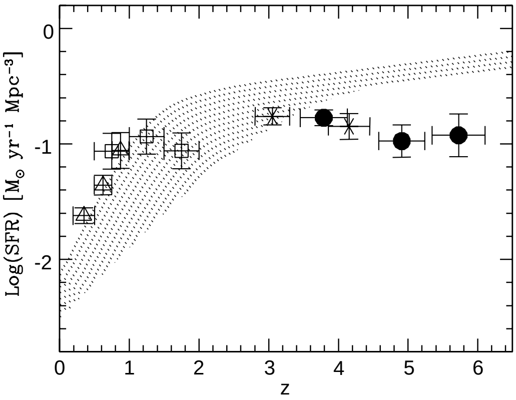

Fig. 2. – Comparison between the observed cosmic SFRH traced by the rest-frame UV luminosity from [10] (dots with error bars) and from [11] (triangle) and the SFRH obtained from GRB FRH properly normalised (shaded area, see text)

*Implications for the progenitors.* Our best models give a *true* (after collimation effect correction) GRB FR of $\sim 5\ 10^{-5}$ y$^{-1}$ for the Milky Way. Based on astronomical arguments we argue that such a FR is close to that of close binary systems consisting of a WR star and a possible massive BH, with periods of hours. These systems are able to generate a massive Kerr BH after the SNIb/c explosion of the WR (helium) star. The observational counterparts of these potential GRB progenitors should be luminous X-ray binaries (*e.g.*, Cyg X-3), which are estimated to be only a few at present in the MW.

*Implications for cosmology.* The finding of the LF properties will shed new light on the connection between the *true* (collimation corrected) energetics of GRBs and their spectral features. This connection, studied for the first time by Ghirlanda *et al.* [13, 14], makes GRBs powerful *standard candles* which hopefully will allow to explore in few years the geometry and the kinematics of the universe beyond $z = 10$ [15-17].

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