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The properties of Long Gamma Ray Burst as derived from an unbiased complete sample of bright bursts

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We selected a complete sub-sample of 58 *Swift* bright long GRBs. The sample was selected considering bursts with favorable observing conditions for ground-based follow-up observations and with the 1-second peak flux above a flux threshold of 2.6 photons cm^{-2} s^{-1} in the 15-150 keV energy band. This sample has a redshift completeness level higher than 90%. Complete samples are at the base of any population study and we used this sample to investigate the properties of long GRBs. In particular, we derived their evolution with cosmic times, focusing on the GRB luminosity function, the prompt emission spectral-energy correlations and the nature of dark bursts. If we assume that long GRBs trace the cosmic star formation, then we can reject the no-evolution scenario in which the GRB luminosity function is constant in redshift. We also confirm the existence of strong $E_{\rm peak}-E_{\rm iso}$ and $E_{\rm peak}-L_{\rm iso}$ correlations for the bursts of this complete sample and of a genuine dark population, with $\sim$ 30% of dark-burst events expected for the whole class of long GRBs. These dark-bursts events seems to generate in much denser metal-rich environments where dust must be present with respect to normal bright events.

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1. Introduction

Long Gamma Ray Bursts (GRB) are associated to the death of very massive stars and, therefore, are associated with star forming regions. Moreover, they are very bright objects that can be detected up to extremely high redshifts: so far we have a secure spectroscopic redshift of z=8.2 and a photometric record holder of z=9.4. At these values, the Universe was very young, less than 10% of its current age. As a result GRBs can be used to trace and study the stellar evolution, the history of the star formation and metallicity enrichment from the local Universe up to the formation of the very first stars. Although it is still not completely clear if GRBs provide un unbiased view of the star formation rate, for sure they provide, at least potentially, an independent and very powerful channel to investigate the Universe at all ages, after the first massive stars have started to form and die. However, if we want to use them to perform statistical investigations of the Universe history as well as to study their intrinsic evolution, we need well defined and unbiased samples of GRBs (or with biases that are well under control). Clearly we also need GRBs with a measured redshift in order to derive their distance/age luminosity and other intrinsic parameters.

To this end we started with the full *Swift* ([**?**]) sample, for which $\sim 1/3$ of the bursts has measured redshift. While this represents an enormous improvement with respect to the pre-*Swift* situation, the sample is still far to be considered complete. Therefore we started from the criteria proposed by [**?**]: i) the burst has been well localized by *Swift*/XRT and its coordinate quickly distributed; ii) the Galactic extinction in the burst direction is low ($A_V < 0.5$); iii) the GRB declination is $-70^\circ < \delta < 70^\circ$; iv) the Sun-to-field distance is $\theta_{\rm Sun} > 55^\circ$; v) no nearby bright stars are present. This increases the completeness level to $\sim 50\%$. We then restricted our sample to GRBs that are relatively bright in the 15-150 keV *Swift*/BAT band, i.e. with a 1-s peak photon flux $P \geq 2.6$ ph s^{-1} cm^{-2}. This corresponds to an instrument that is ~ 6 times less sensitive than *Swift*. 58 GRBs match our selection criteria up to May 2011 (see [**?**]). 52 of them have measured redshift so that our completeness level is 90%. Moreover, for 3 of the other 6 bursts 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 long GRBs with known redshift.

2. Long GRBs: evolution and/or low metallicity environment are needed

We derived the GRB luminosity function (LF) by jointly fitting the observed differential number counts in the 50–300 keV band of BATSE ([**?**]) and the observed redshift distribution of bursts in our sample. 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. It is worth to note that the best-fit parameters provide a good fit also 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. We explore two general expressions for the GRB LF: a single power-law with an exponential cut-off at low luminosity and a broken power-law LF ([**?**]).

The results are shown in figure **??**. The no-evolution scenario, in which we assume that long GRBs trace the cosmic star formation and that their LF is constant in redshift, clearly does not

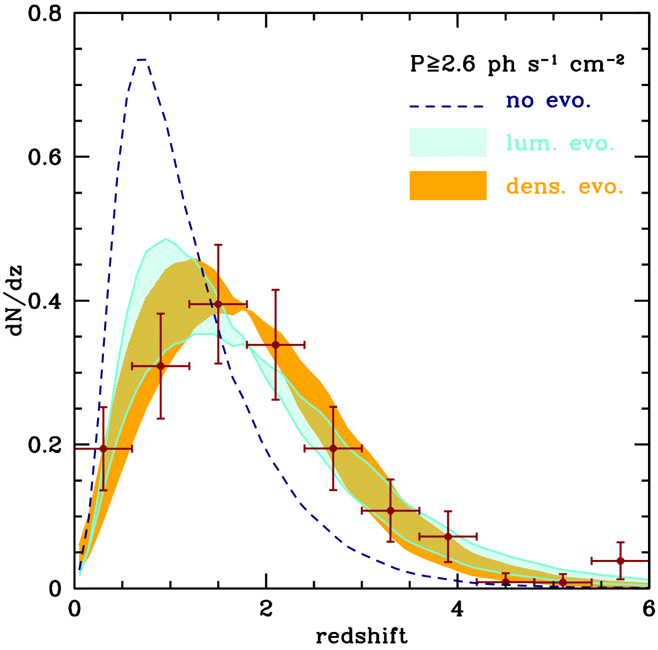

Figure 1: Normalized redshift distribution of GRBs with $P \geq 2.6$ ph s^{-1} cm^{-2}. Data points show the observed redshift distribution. The dashed line shows the expected distribution for the no-evolution case. Results of luminosity and density evolution models are shown with the hatched and dark shaded regions.

provide a good representation of the observed redshift distribution of our sample, confirming previous findings. Therefore, we considered two evolution scenarios: i) a luminosity evolution model in which high-z GRBs are typically brighter than low-z bursts and, ii) a density evolution model, leading to an enhancement of the GRB formation rate with redshift. We find that both models can reproduce the observed redshift distribution; implying that either the typical burst luminosity increases as $(1+z)^{2.3\pm0.6}$ or the GRB rate density as $(1+z)^{1.7\pm0.5}$ 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 0.3 $Z_\odot$ in order to account for the observations assuming no evolution of the GRB LF ([**?**]).

We then used this complete sample of bright long GRBs to investigate the correlations between their spectral peak energy $E_{\rm peak}$, the isotropic energetics $E_{\rm iso}$ and the isotropic luminosity $L_{\rm iso}$ (see [**?**]). We find strong $E_{\rm peak}-E_{\rm iso}$ and $E_{\rm peak}-L_{\rm iso}$ correlations for the bursts of this complete sample, with only one outlier, GRB061021. Their slopes, normalizations and dispersions are consistent with those found with the whole sample of bursts with measured redshift and $E_{\rm peak}$. The biases present in the total sample commonly used to study these correlations do not affect their properties. We also find that there is no evolution with redshift of the $E_{\rm peak}-E_{\rm iso}$ and $E_{\rm peak}-L_{\rm iso}$ correlations ([**?**]). By performing Monte Carlo simulations under different assumptions for their LF we studied the possible effects caused by the flux-limit selection on this $E_{\rm peak}-L_{\rm iso}$ correlation. If we assume that there is no correlation, we are unable to reproduce it as due to the flux limit threshold of our complete sample. We can reject the null hypothesis at more than 2.7 σ level of confidence ([**?**]).

Using the *Swift* X–ray Telescope data we derive the intrinsic absorbing X–ray column densities of these GRBs ([**?**]). Their distribution has a mean value of $\log(N_H/\mathrm{cm}^{-2}) = 21.7 \pm 0.5$, with a mild increase of the intrinsic column density with redshift, due to the contribution of intervening systems along the line of sight. We have also established the existence of a genuine dark population with $\sim 30\%$ of dark-burst events expected for the whole class of long GRBs ([**?**]). The redshift distribution and the prompt properties of this population of dark-bursts are similar to the one of the whole sample. At the same time their de-absorbed X-ray flux is slightly higher than the one of the non-dark events, while their optical flux is at the lower tail of the optical flux distribution. All these properties suggest that dark-burst events generate in much denser environments with respect to normal bright events. In agreement with previous results, we can therefore exclude the high-z and the low-density scenarios as the cause of their darkness. The major cause of the optically dark events is the dust extinction ([**?**]). This is also supported by the very tight correlation between the GRB darkness and their high X-ray column densities ([**?**]). Finally, we investigate the relation between the GRB prompt and afterglow emission properties ([**?**]). We find that the X-ray luminosities correlate with the $E_{\rm iso}$, $E_{\rm peak}$ and $L_{\rm iso}$ with a significance that decreases over time suggesting that the X-ray light curve is dominated by the prompt (afterglow) emission at early (late) time.

All these results immediately show the importance of having well defined criteria to select a complete sample of GRBs.

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