Probing cosmological parameters with GRBs

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Abstract. In light of the recent finding of the narrow clustering of the geometrically-corrected gamma-ray energies emitted by Gamma Ray Bursts (GRBs), we investigate the possibility to use these sources as standard candles to probe cosmological parameters such as the matter density $\Omega_m$ and the cosmological constant energy density $\Omega_\Lambda$. By simulating different samples of gamma-ray bursts, based on recent observational results, we find that $\Omega_m$ (with the prior $\Omega_m + \Omega_\Lambda = 1$) can be determined with accuracy $\sim 7\%$ with data from 300 GRBs, provided a local calibration of the standard candles be achieved.

INTRODUCTION

Recent studies have pointed out that Gamma-Ray Bursts (GRBs) may be considered as standard cosmological candles. The prompt $\gamma$-ray energies of GRBs, after correction for the conical geometry of the jet, result clustered around a mean value of a few $10^{50}$ erg [2].

Since the discovery that GRBs lie at cosmological distances, about 30 redshifts have been measured. Apart from the controversial case of GRB 980425, possibly associated with the nearby supernova SN1998bw (at $z = 0.0085$), all other redshifts are spread within the wide $0.17-4.5$ range. Therefore GRBs could be good candles to probe cosmological parameters [4] [5].

GRBs are thought to be associated with the death of massive (and short lived) stellar progenitors. Therefore the rate of GRB events per unit cosmological volume should be a tracer of the global history of star formation.

Hence, we have now all the information necessary to perform simulations of GRB distributions in a given cosmological model. Universal parameters such as the matter density fraction $\Omega_m$ and the cosmological constant energy fraction $\Omega_\Lambda$, can be constrained by fitting the Hubble diagrams corresponding to such simulated distributions. It is the aim of this paper to simulate different GRB distributions and investigate their ability to determine the cosmological parameters $\Omega_m$ and $\Omega_\Lambda$. Both universes with and without a cosmological constant $\Lambda$ will be considered.

TO START: A KS TEST

First, in order to show what we are aiming at, we performed a Kolmogorov-Smirnov (KS) test on two data sets made of 300 GRBs simulated in two different cosmological
models, one with $\Omega_m = 1$ and $\Omega_\Lambda = 0$ and the other with $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$, but both with a Hubble constant $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$ (as it will be assumed throughout the paper). We assume that GRBs are indeed standard candles with true prompt $\gamma$-ray energy released, $E_\gamma$, following a Gaussian distribution in its logarithm with mean $\mu = 50.7$ (if $E_\gamma$ is expressed in erg units) and $\sigma = 0.3$ (corresponding to a multiplicative factor of 2) [2], and that they are distributed in the universe according to the model of star formation rate $R_{SF1}(z)$ reported in [3], which matches the log $N$ – log $P$ relation (GRB number counts vs. peak photon flux) obtained with BATSE data. Applying the KS test on the redshift distributions, we found that the probability that the two data sets are drawn from the same distribution is $Q_{KS} = 2.48 \cdot 10^{-14}$.

DATA SET SIMULATIONS IN A $\Lambda = 0$ COSMOLOGY

We consider now a $\Lambda = 0$ cosmology, in which the only contribution to the density parameter is given by $\Omega_m$. We assume for GRBs the same energy distribution as for the KS test. However, the assumed mean value is not relevant for our investigation, since it is the dispersion value that constrains the cosmological density parameter.

The standard candle energy is related to the fluence of the burst $f_\gamma = E_\gamma (1 + z)/ (4 \pi d_L^2(z))$ via the luminosity distance $d_L(z)$. In order to have a linear propagation of errors throughout our simulations, we choose to construct with GRBs a Hubble diagram $\log d_L^2(z)$, since the distribution of the parameter $\log d_L^2$ is the same of that of $\log E_\gamma$, and therefore it is Gaussian.

In order to study the ability of GRBs in probing the cosmological parameters as a function of their number, we have simulated different samples with $N_{GRB} = 10, 30,$
TABLE 1. Mean values of the fitted cosmological density parameters $\Omega_m$ and $\Omega_\Lambda$, of their error $\Delta\Omega$ and their dispersion $S_\Omega$ obtained by fitting $10^2$ GRB sample realizations with $N_{\text{GRB}}$ distributed according to function $R_{SF1}(z)$ of [3] in an Einstein-de Sitter universe ($\Omega_m = 1$, left) and in a flat universe with input values $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$ (right).

| $N_{\text{GRB}}$ | $<\Omega_m>$ | $<\Delta\Omega_m>$ | $S_\Omega$ |
|-----------------|-------------|-------------------|-----------|
| 10              | 0.9983      | 0.2997            | 0.3097    |
| 30              | 1.0158      | 0.1895            | 0.1993    |
| 100             | 0.9937      | 0.0993            | 0.1108    |
| 300             | 0.9959      | 0.0599            | 0.1108    |
| 1000            | 1.0009      | 0.0332            | 0.0351    |

100, 300 and 1000. Moreover, in order to be free from statistical fluctuations, we have performed $10^2$ realizations of each of these samples.

The simulation of a GRB consists of the random sampling of both the redshift $z$ and the true $\gamma$-ray energy released $E_\gamma$, according to the respective adopted distributions. Given a cosmological model, from these coupled values we obtain the corresponding value for the parameter $\log d_L^2$, which we plot on the Hubble diagram as a function of $z$. At this point we perform a $\chi^2$ minimization of the simulated data to see with which accuracy the fit reproduces the input cosmology. The measurement error on $\log d_L^2$ is assumed to be $\sigma = 0.3$. The mean results of our repeated fits in an Einstein-de Sitter universe ($\Omega_m = 1$) are reported in the left side of Table 1.

DATA SET SIMULATIONS IN A $\Lambda$-DOMINATED COSMOLOGY

We move now to a $\Lambda$-dominated cosmology, in which the contributions to the density parameter are given by the mass density, $\Omega_m$, and by the cosmological constant energy density, $\Omega_\Lambda$. In light of the recent observations of the cosmic microwave background anisotropy [1], we put the prior of a flat universe $\Omega_m + \Omega_\Lambda = 1$.

Again, in order to study the ability of GRBs in probing the cosmological parameters in a $\Lambda$-dominated universe, we have simulated $10^2$ realizations of GRB samples with $N_{\text{GRB}} = 10, 30, 100, 300$ and 1000. The $\chi^2$ minimization of the resulting Hubble diagrams has been performed considering $\log d_L^2$ depending only on the fit parameter $\Omega_m$, i.e., using the relation $\Omega_\Lambda = 1 - \Omega_m$. The right side of Table 1 reports the general results of our repeated fits for a flat cosmology with input values $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$ (which are those adopted in [2]).

Focusing on the samples with $N_{\text{GRB}} = 300$, which represent the future data set expected from the Swift satellite experiment, Figure 2 shows one of the Hubble diagrams $\log d_L^2 - z$ obtained with the simulations (left), together with the distribution of the best fit values of the matter density fraction $\Omega_m$ for $10^3$ sample realizations (right).

Finally, we must remark that the analysis in [2] assumes of course a particular set of cosmological parameters to derive the standard $\gamma$-ray energy of GRBs. To avoid a circular logic we should assume a candle calibration with a local sample of sources, a prospect which can now be considered possible in light of the discovery of the near GRB
FIGURE 2. Left: Hubble diagram log\(d_L^2 - z\) with data simulated for a sample of 300 GRBs in a flat universe with density parameters \(\Omega_m = 0.3\) and \(\Omega_\Lambda = 0.7\). The solid curve shows the function log\(d_L^2(z)\) in the assumed cosmology, while the dashed curves give the dispersion about the best fit parameter (upper curve corresponds to lower \(\Omega_m\)). Right: Histogram with the distribution of the best fit values of the matter density \(\Omega_m\) for \(10^3\) realizations of a sample of 300 GRBs in a flat universe with density parameters \(\Omega_m = 0.3\) and \(\Omega_\Lambda = 0.7\). The distribution has a mean \(<\Omega_m>\) = 0.3001, a median \(\Omega_m\)\(_{\text{med}}\) = 0.3002, a dispersion \(S_{\Omega_m}\) = 0.0228, and a kurtosis \(k_{\Omega_m}\) = 3.0993, to be compared with the value of a Gaussian distribution, i.e., 3.

030329, with redshift as low as \(z = 0.1685\).

CONCLUSIONS

We have simulated different samples of GRBs adopting \(\gamma\)-ray energy and redshift distributions consistent with recent observational results, in order to investigate their ability to probe cosmological parameters such as the density fractions \(\Omega_m\) and \(\Omega_\Lambda\). Our result is that in a \(\Lambda\)-dominated flat universe the accuracy in the determination of the matter density \(\Omega_m\) is \(\sim 40\%\) for a sample with \(N_{\text{GRB}} = 10\) and an excellent \(\sim 4\%\) for \(N_{\text{GRB}} = 1000\).

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