PROCEEDINGS OF SCIENCE

Gamma ray bursts (GRBs) as probes of Cosmological Parameters

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Dark energy (the cosmological constant) is the basic constituent of the universe today that permeates all space, and is the most widely accepted theory to explain recent observations that the universe is expanding at an accelerated rate. Observations of GRBs, the most powerful cosmic explosions and which have been detected up to a photometric redshift z = 9.4, can play a crucial role to shed lights on dark energy and other cosmological parameters when the universe was much younger than today. GRBs might be good distance indicators, similar to Type Ia supernovae which have been detected only up to a redshift z = 1.914, once its emission can be characterized as standard candles. We study a sample of GRBs with known redshift and explore their observational properties to probe cosmological parameters by using the phenomenological models to consider GRBs as standard candles.

SALT Science Conference 2015 -SSC2015-
1-5 June, 2015
Stellenbosch Institute of Advanced Study, South Africa

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PoS(SSC2015)066

1. Introduction

Long-duration gamma-ray bursts (GRBs) are the most powerful electromagnetic transient phenomena in the universe in which their progenitors are associated with the explosive death of massive stars. Since their collimation corrected energy in gamma rays is more than 10^{52}erg, released in a few tens of a second, and their observed redshift distribution covers a wide range of photometric redshift up to z = 9.4 [1]. This Burst may allow us to look into a high redshift space beyond what is provided by SNe Ia studies, for the purpose of constraining the cosmological parameters when the universe was much younger than today. GRBs would be the ideal device to explore the characteristics of dark energy and measure it over a wide range of redshifts or scale factors. For homogeneous, isotropic and flat cosmologies, the density parameter Ω_σ evolving with the redshift [2] is given by

$$\Omega_\sigma(z) = \frac{\rho_\sigma(z)}{\rho_c(z)} = \Omega_{\sigma_0}(z)\frac{(1+z)^{n_\sigma}}{E^2(z)}, \tag{1.1}$$

where $n_\sigma = 3(1+\omega_\sigma)$ stands for different equation of states of the universe (i.e. for radiation $n_r = 3$, matter $n_m = 4$, and dark energy $n_{de} = 0$), Ω_{σ_0} is the current density parameter, $E^2(z) \equiv H_0^2/H^2 = \Omega_{m_0}(1+z)^3 + \Omega_{r_0}(1+z)^4 + \Omega_{de_0}a^{-3(\omega_{de}(z)+1)}$ is the expanding Hubble parameter and H_0 is the Hubble constant. Fig. 1 shows the three domination density components of the universe at different

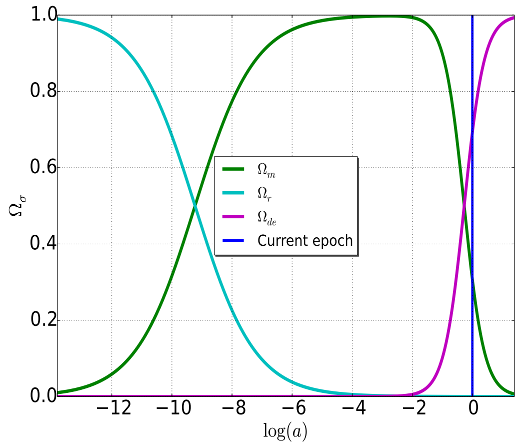

Figure 1: The density components of the universe at different scale factor a = $1/(1+z)$. The current radiation density $\Omega_{r_0} = 3\times10^{-5}$, matter $\Omega_{m_0} = 0.306$ and dark energy $\Omega_{de_0} = 0.693$.

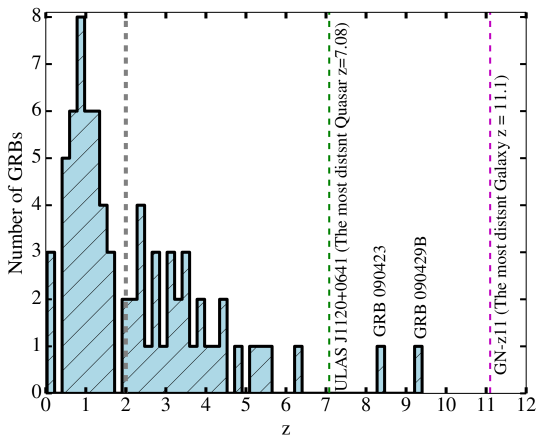

Figure 2: The histogram of the distribution of redshift obtained for 74 samples of long GRBs [3], 090429B [1], GRB 090423 [4], distant Quasar ULAS J1120+0641 (green vertical dashed line) [5] and distant Galaxy GN-z11 (magenta vertical dashed line) [6].

epoch. At high redshift, the universe dominated by radiation (cyan line). As the universe expands, there was a time when the matter energy density (green line) became comparable with the radiation energy density. At lower redshifts, matter dominates over radiation and ultimately the dark energy density (magenta line) dominates over non-relativistic matter. This is because, when the universe expands, the matter energy density falls as the third power while the energy density contributed by the cosmological constant does not change. We certainly can use the GRB observable of the isotropic equivalent-radiated energy $E_{iso} = 4\pi D_L^2(z,\Omega_{de},\Omega_m,\Omega_r,H_0)S_{bolo}(1+z)^{-1}$, to constrain the cosmological parameters through the equation of luminosity distance $D_L(z,\Omega_{de},\Omega_m,\Omega_r,H_0) = (1+z)cH_0^{-1}\int_0^z E(z)^{-1}dz$ and the bolometric fluence S_{bolo} of the total time integrated sources. As shown in Fig. 2, the highest photometric redshift GRB found to-date is z = 9.4 for GRB 090429B [1]. This compares well with the most distant quasar with a confirmed redshift of z = 7.08 [5] and help in the determination of the cosmological parameters. The earliest galaxy candidate GN-z11 (z = 11.1) in the universe is now detected by Hubble Space Telescope Grism Spectroscopy [6]. Indeed, the high redshift burst disagree with recent claims that current GRB observations can be used to constrain strongly the cosmic star formation history.

2. GRB Hubble diagram

The investigation of dark energy and its nature has become a major issue, especially after the measurement of the Hubble diagram of SNe Ia, which has revolutionized cosmology, showing that the current expansion of the universe is accelerating [7]. This provides convincing evidence for the

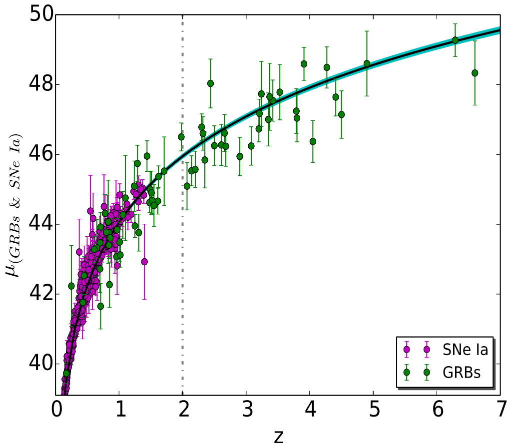

Figure 3: The Hubble diagram of 67 GRBs [8] (green) and 557 SNe Ia [9] (magenta) data are jointly fitted by the distance modulus (μ) of SNe Ia and GRBs $\mu_{GRBs\ \&SNe\ Ia} = (44.06 \pm 0.04)z^{(0.06\pm5\times10^{-5})}$ and χ^2/dof = 78.28/622 with the errors referring to the 95% confidence level.

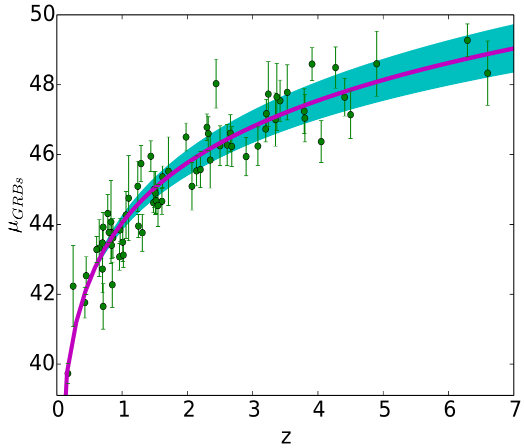

Figure 4: The Hubble diagram of 67 GRBs fitted by the power law model $\mu_{GRBs} = (44.05 \pm 0.2)z^{(0.06\pm4.8\times10^{-3})}$ and χ^2/dof = 28.7/65 with the errors referring to the 95% confidence level.

existence of dark energy. The Hubble diagram is a plot of distance versus redshift with the slope giving the expansion history of our universe that relies on the cosmological parameter (Ω_r, Ω_m, Ω_{de} and H_0) dominated the universe at different rate. As illustrated in Figs 3 and 4, GRBs give a much longer lever arm for measuring changes in the slope of the Hubble diagram than the SNe Ia, which makes them a good candidate to measure the cosmological parameters at high redshift.

3. Data analysis

In our spectral analysis, we have chosen samples of 68 and 74 long GRBs with known redshift by Amati et al. 2008 (A2008) [10] and Ghirlanda et al. 2008 (G2008) [3], respectively. Among these, X-Ray Flash (XRF), GRB 050416A and GRB 020903 are not considered because their rest-frame T_{90} duration is smaller than 2 s. All of the bursts used in this study were triggered by the satellites BATSE, BeppoSAX , HETE-2, Konus and *Swift* which provide the estimates of spectral parameters and flux.

3.1 Observational correlation between E_{iso} and $E_{i,peak}$

Since 2002, there has been sustained interest in using the correlations of the spectral observables of GRBs for standard candles. A correlation between the isotropic equivalent-radiated energy (E_{iso}) and the source frame intrinsic peak energy ($E_{i,peak}$) given by $E_{i,peak} = E_{peak}(1+z)$ was discovered by A2008 [11], where E_{peak} is a peak energy of the energy density νF_ν spectra. This relation is analogous to the peak luminosity and the rate of decline of the light curve of the Type Ia supernovae and could therefore be used as a standard candle for cosmology [7]. To describe the observational Amati relation, we have considered a power law: $E_{i,peak} = k\left(E_{iso}/10^{52}\text{erg}\right)^{\alpha}$, where k (keV/erg) is a normalization constant and α is the slope of the fitting model. In Fig. 5,

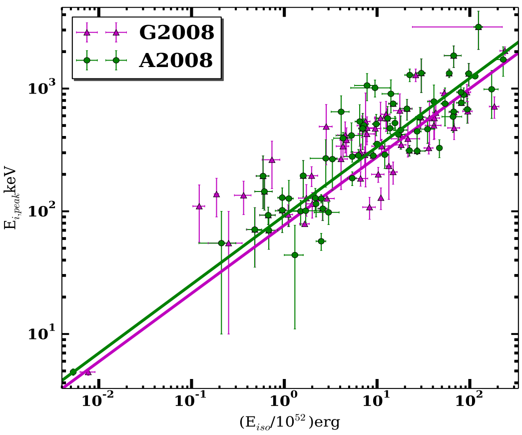

Figure 5: Amati correlation of 68 GRBs from A2008 [10] and 74 from G2008 [3] are fitted by power law.

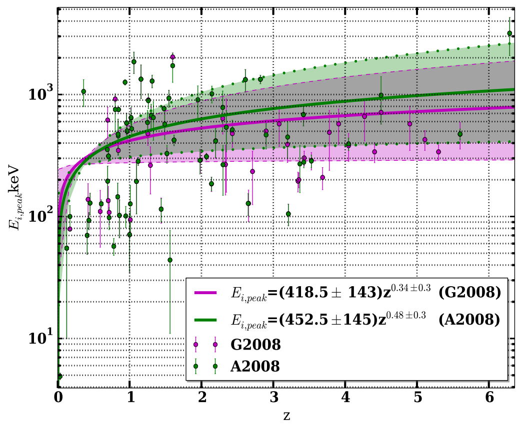

Figure 6: The cosmic evolution of the $E_{i,peak}$ distribution with respect to the redshift.

the analysis shows a sample of GRBs with measured redshift which reveals a correlation between their peak spectral energy and isotropic equivalent-radiated energy. The green line is the power law best fit (obtained by weighting each point by its error on both $E_{i,peak}$ and E_{iso}) of A2008 samples of GRBs by $E_{i,peak} = (92.16\pm6.16)\left(E_{iso}/10^{52}\text{erg}\right)^{0.56\pm0.02}$ with the reduced $\chi^2_{red} = 6.4$ and the Pearson's correlation coefficient ($\rho = 0.696$ and chance probability $P_{chance} = 4.3\times10^{-11}$). The magenta line is the best fit of the G2008 sample with $E_{i,peak} = (77.06\pm7.8)\left(E_{iso}/10^{52}\text{erg}\right)^{0.556\pm.028}$ with the reduced $\chi^2_{red} = 7.1$ ($\rho = 0.71$ and $P_{chance} = 1.53\times10^{-12}$). This relation shows the discrepancy of index about 0.07 to the one found by Heussaff et al. (2013) [12] from a sample of Fermi and *Swift* 43 GRBs fitted by $E_{i,peak} = 118\left(E_{iso}/10^{52}\text{erg}\right)^{0.486}$. In the sample for the same GRBs, there are some $E_{i,peak}$ and E_{iso} values which are different in the compilation of A2008 and G2008 analysis. Accordingly, the fitting slope for A2008 (0.56 ± 0.02) and G2008 (0.556 ± 0.028) are compatible except the normalization constant. This suggests that we need to figure out the proper calibration including the calculation of error propagation on the parameters and data selection for the observables analysis before using them for the correlation purpose. Other appropriate cosmological parameters must also be addressed before using GRBs as standard candles in the field of cosmology. Fig. 6 shows, the distribution of intrinsic peak energy of A2008 and G2008 data with respect to the redshift of the bursts. The magenta and green curved line indicates, the power law fit to the G2008 and A2008 data. The dispersion of the data around the power law fit, indicated by the reduced chi-square is extremely large due to the sample dispersion and the correlation for both samples are also very low, however the distribution of intrinsic peak energy is more populated at low redshift.

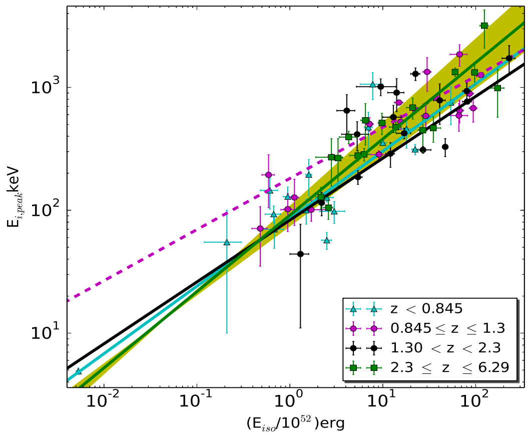

Figure 7: E_{iso}-$E_{i,peak}$ relation for different redshift, for the data samples of 68 GRBs from A2008. The fitting parameters are given in Table 1.

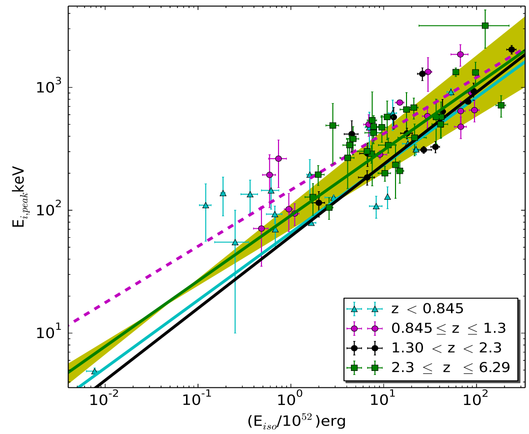

Figure 8: E_{iso}-$E_{i,peak}$ relation for different redshift, for the data samples of 74 GRBs from G2008. The fitting parameters are given in Table 2.

Prefactor	slope	χ^2_{red}	redshift	No.
85.3 ± 6.9	0.55 ± 0.02	5.7	$z < 0.845$	17
181.4 ± 41.8	0.42 ± 0.06	6.2	$0.845 \leq z \leq 1.3$	17
83.2 ± 29.3	0.50 ± 0.10	6.7	$1.30 < z < 2.3$	17
91.1 ± 16.5	0.62 ± 0.06	2.7	$2.3 \leq z \leq 6.29$	17

Table 1: The power law fitting parameters for A2008 E_{iso}-$E_{i,peak}$ relation for different redshift.

Prefactor	slope	χ^2_{red}	redshift	No.
65.8 ± 6.8	0.55 ± 0.04	6.0	$z < 0.845$	18
146.1 ± 45.2	0.46 ± 0.09	10.0	$0.845 \leq z \leq 1.3$	15
61.4 ± 24.96	0.59 ± 0.10	6.8	$1.30 < z < 2.3$	13
90.6 ± 19.96	0.53 ± 0.07	3.9	$2.3 \leq z \leq 6.29$	28

Table 2: The power law fitting parameters for G2008 E_{iso}-$E_{i,peak}$ relation for different redshift.

We recognized that there is no statistically significant evidence for redshift dependence on normalization constant k and slope α in any of the correlation relations tested for different redshift intervals (Fig. 7 and Fig. 8). It is also worth to investigate if any evolution with redshift can affect the E_{iso} - $E_{i,peak}$ correlation defined by this sample. For the high redshift span of $2.3 \leq z \leq 6.29$ and $2.3 \leq z \leq 6.29$, A2008 and G2008 samples of GRBs are well fitted by a power law, respectively.

4. Summary

Using GRBs as cosmological probes to measure distances in the early universe will enable us to understand the universe's mysterious expansion over time. We have recognized that long-duration GRBs hold considerable promise as probes of the high-redshift universe. Here, the data and analysis of 68 GRBs with redshift that were collected from the previous work of A2008 and 74 GRBs from G2008 published work was presented. The main focus was laid upon the GRBs observables E_{iso} and $E_{i,peak}$ correlation. The correlation between E_{iso} and $E_{i,peak}$ for both A2008 and G2008 samples with the best fit power law index 0.56 $\pm$ 0.02 (68 GRBs data) and 0.556 $\pm$ 0.028 (74 GRBs data) is scrutinized, respectively. We have also divided the GRB sample into redshift bins and have compared the slope of the $E_{i,peak}$ correlation for each redshift bin. We find no correlation between the spectral parameters and the redshift nor between the peak energy and the spectral photon index. A proper evaluation and calibration of the correlations may facilitate the use of GRBs as standard candles constraining the expansion history of the universe for known redshifts. In our future work, we will find the best E_{iso}-$E_{i,peak}$ correlation and other relation with a minimum scattering outlier by using the data analysis of the Fermi-LAT at high energy to constrain cosmological parameters.

5. Acknowledgements

This work was supported in part by an MWGR 2015 grant from the National Research Foundation with Grant No. 93273. I want to thank also the organizers of the Science with SALT 2015 conference for giving me the opportunity to present this work, and for their financial support to attend the conference.

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