Calibrating Gamma Ray Bursts from SN Ia

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Abstract. To consider GRBs as standard candles, the circularity problem should be surmounted. To do this GRBs are calibrated at low redshifts using SNIa data and then extrapolating the calibration to higher redshifts. In this work we apply GRBs calibration to estimate the Hubble parameter, $H(z)$, from the luminosity distance extracted from the calibration and, knowing $H(z)$, we study the parameter $w(z)$ of the equation of state of dark energy.

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INTRODUCTION

In 1998 astronomical observations provided evidence of a repulsive side of gravity. Measurements of the brightness of Type Ia Supernovae (SNIa) pointed to an accelerated expansion of our universe. This expansion has been attributed to an energy component (dark energy) with negative pressure which dominates the universe at late times and causes the observed accelerated expansion. Therefore one of the most important objective in cosmology is to understand the nature of dark energy.

SNIa, that are standard candles, have been considered to be a powerful probe to study this mysterious phenomenon, however, SNIa are plagued with extinction from the interstellar medium, and hence the current maximum redshift of SNIa is only about $z \simeq 1.755$. On the other hand, the redshift of the last scattering surface of cosmic microwave background (CMB) is about $z \simeq 1090$ [1]. Therefore, there is a wide breach between the redshift of SNIa and CMB. So, the observations at intermediate redshift are important to discard cosmological models.

Recently, Gamma-Ray Bursts (GRBs) have been proposed to be a complementary probe to SNIa. So far, GRBs are the most violent and bright explosions in the universe. Their high energy photons in the gamma-ray band are almost immune to dust extinction, in contrast to supernovae. Up to now, there are many GRBs observed at $0.1 < z \leq 8.1$, whereas the maximum redshift of GRBs is expected to be 10 or even larger [2]. The problem is that GRBs appear to be anything but standard candles: they have a very wide range of isotropic equivalent luminosities and energy outputs. Suggestions have been made to calibrate them by using correlations between various properties of the prompt emission, and in some cases also the afterglow emission. Nevertheless, the calibration of the observed correlations require the assumption of a cosmological model creating a circularity problem. Moreover, there are scarce low redshift GRBs data. However, if one assumes that once leaving their source, light rays should propagate in the same way throughout cosmic spacetime, then we can calibrate GRBs at low redshift using the known data for SNIa.

In the next section we show briefly how to calculate distances to astrophysical objects and how to link their luminosity to the speed of expansion of the Universe. Next we show how to calibrate GRBs using SNIa; we use a 25 sample of GRBs data given in [3] and a 27 sample of the SNIa data from [4] with $0.359 < z < 1.755$. With this calibration we have two posibilities: 1) to study the behavior of the parameter of the equation of state of dark energy for a redshift range wider than before, or 2) to determine the cosmological parameters at higher redshifts, this could be pending for future work.

ASTROPHYSICAL DISTANCES MEASUREMENT

The luminosity distance d_L used at observations is defined as

$$d_L^2 \equiv \frac{L_s}{4\pi F}, \tag{1}$$

where L_s is the absolute luminosity of the object and F is the observed flux during a time t. For Friedmann-Lemaître-Robertson-Walker (FLRW) flat spacetime, the luminosity distance can be written as

$$d_L = \frac{c(1+z)}{H_0} \int_0^z \frac{d\tilde{z}}{E(\tilde{z})}, \tag{2}$$

where

$$E(z) \equiv \frac{H(z)}{H_0}. \tag{3}$$

H_0 is the present Hubble constant and c is the velocity of light.

From the above equation the Hubble parameter can be expressed in terms of the luminosity distance as

$$H(z) = \left\{ \frac{d}{dz} \left(\frac{d_L(z)}{c(1+z)} \right) \right\}^{-1}. \tag{4}$$

On the other hand, the luminosity distance can be obtained observationally from μ, the observed distance module with

$$\mu_0 \equiv m - M = 5 \log d_L + 25, \tag{5}$$

where m is the apparent magnitude and M is the absolute magnitude. So, with Eqs. (4) and (5) we can obtain $H(z)$ from observational data.

Therefore, the main quantity to find is the luminosity distance d_L as a function of the redshift z of distant objects. To extract the real distances a standard rule to compare is needed. This is a standard candle, objects in the universe with a well calibrated intrinsic luminosity. Type Ia supernovae are these kind of objects [5] and it has to do with their origin, as a white dwarf that accreting matter (from a companion star, for instance) gets to the Chandrasekhar limit mass.

Then, to enlarge the range of redshifts in probing cosmological models using Gamma-ray-bursts (GRBs), as a first step we must establish under which parameters can GRB be considered as reliable standard candles or under what conditions can be calibrated to avoid circularity problems so we can use them in the study of dark energy.

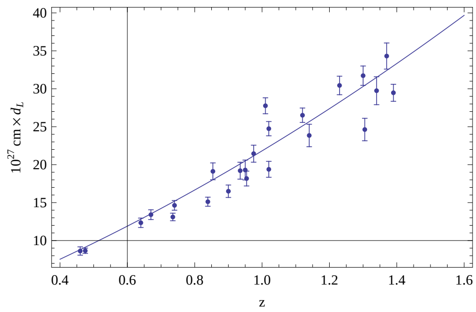

FIGURE 1. Luminosity distance adjustment for 27 SNIa data from [4]. The best fit is given by Eq. (6) with $R^2 = 0.97$.

CALIBRATING GAMMA-RAY BURST.

GRBs can be considered as distance indicators if they can be calibrated at low redshifts; however few data are available at these redshifts. To solve this problem, following [6], we extrapolate the existing relation d_L vs z for SNIa up to $z < 1.7$ to GRBs.

We use the distance module, μ_0, of 27 SNIa reported in Riess et al. (2007) in the range 0.359 <z <1.75 to calculate the luminosity distance using Eq. (5).

Adjusting observational data we found a formula for the luminosity distance in the redshift range $0.359 < z < 1.755$, this is

$$\frac{d_L}{10^{27}cm} = (16.85 \pm 2.76)z + (4.97 \pm 2.45)z^2. \tag{6}$$

It is not assumed any cosmological model at this stage, but just that SNIa are standard candles. The corresponding fit is shown in Fig. (1).

Then, we apply Eq. (6) to 16 GRBs with redshift $z < 1.755$ to obtain the total collimation-corrected energy of the GRB, $E_\gamma = 4\pi d_L^2 S_{bolo}(1+z)^{-1} F_{beam}$, where S_{bolo} is the bolometric fluence estimated in 1-10000keV energy range in GRB rest frame and F_{beam} is a beaming factor related with the jet opening angle. On the other hand, it is also reported the peak energy of the νF_ν spectrum. The observed peak energy value, $E_{p,obs}$, must be multiplied by $1+z$ as a correction to the redshift of the spectrum, so we use $E_{peak} = (1+z)E_{p,obs}$.

Ghirlanda et al. [7] discovered a tight correlation between E_{peak} and E_γ. This is an improvement on (and combination of) both the E_γ =constant relation of Bloom et al. [8] and the $E_{peak} - E_{\gamma,iso}$ relation of Amati et al. [9]. The Ghirlanda relation is given by

$$\frac{E_\gamma}{10^{52}erg} = 3.41 \times 10^{-6} \left(\frac{E_{peak}}{1keV}\right)^{1.63}. \tag{7}$$

We verify that the Ghirlanda relation is fulfilled by the 16 GRBs with z <1.755 and this expression is extrapolated to 25 GRBs with higher redshifts, up to $z < 5.6$.

For each GRB with $z = z^i$ we have the observed S_{bolo} in units of erg cm^{-2}, the dimensionless F_{beam} and the observed $E_{p,obs}$ in keV. Then, using Eq. (7) and $E_\gamma =$

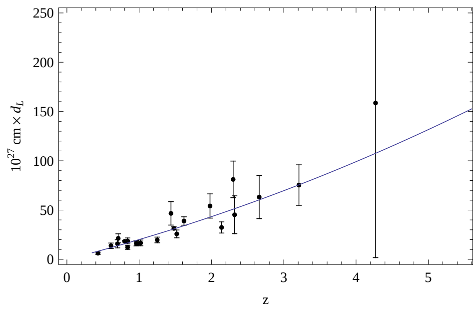

FIGURE 2. Luminosity distance adjustment for the GRBs' data from [3], derived using the Ghirlanda relation; the best fit is given by Eq. (10) with $R^2 = 0.86$.

$4\pi d_L^2 S_{bolo}(1+z)^{-1}F_{beam}$, the observed luminosity distance can be derived as

$$d_L(z^i) = 10^{23}cm\sqrt{\frac{3.41}{4\pi F^i_{beam}S^i_{bolo}}}(E^i_{p,obs})^{0.815}(1+z^i)^{1.315}. \quad (8)$$

With the error propagation (shown in Fig. 2) calculated according to

$$(\Delta d_L(z))^2 = \left(\frac{\partial d_L(z)}{\partial S_{bolo}}\sigma_{S_{bolo}}\right)^2 + \left(\frac{\partial d_L(z)}{\partial F_{beam}}\sigma_{F_{beam}}\right)^2 + \left(\frac{\partial d_L(z)}{\partial E_{p,obs}}\sigma_{E_{p,obs}}\right)^2, \quad (9)$$

where σ_i is the uncertainty related to each data, as reported in [3]. From Eq. (8) and the data of GRBs in the range $0.359 < z < 5.6$, we obtained the luminosity distance given by (see Fig. 2)

$$\frac{d_L}{10^{27}cm} = (18.55 \pm 5.73)z + (1.56 \pm 1.87)z^2. \quad (10)$$

Substituting Eq. (10) into Eq. (4), we obtained $H(z)$ and then we derived the dark-energy equation of state parameter $w(z)$ from (plotted in Fig. 3)

$$w(z) = \frac{\frac{2}{3}(1+z)\frac{d\ln H}{dz} - 1}{1 - \frac{H_0^2}{H^2}\Omega_{0m}(1+z)^3}. \quad (11)$$

CONCLUSIONS

In the present work, with the help of the sample of 27 SN Ia from Riess et al. (2007) [4], we calibrated 25 GRBs with the well-known Ghirlanda relation, obtaining a cosmology-independent calibration. For a sample of 9 GRBs we extended the Ghirlanda relation to higher redshifts. It can be used to constraint cosmological models or to study the behaviour of the parameter of the equation of state for dark-energy in terms of the redshift, $w(z)$, without the circularity problem.

From the empirical luminosity distance, $d_L(z)$, Eq. (10) we obtained the corresponding Hubble function and then $w(z)$. We noticed that Eq. (11) for $w(z)$ is not valid for

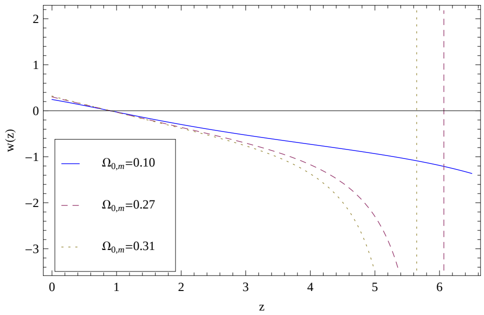

FIGURE 3. The plot for $w(z)$, as a function of the redshift Eq. (11) assuming $H_0 = 49.01$km s^{-1}Mpc^{-1} as the present value of the Hubble parameter that is obtained from our adjust, Eq. (10).

all redshifts z, but there is a critical z_c where the factor $[1-(H_0/H(z))^2\,\Omega_{0m}(1+z)^3]$ becomes zero, and then $w(z)$ diverges. The value of z_c depends on the chosen Ω_{0m} and H_0 and therefore the behavior of $w(z)$ depends strongly on the assumed Ω_{0m}: this is the influence of dark matter on dark energy [10]. In Fig. 3 it is shown the behaviour of $w(z)$, for lower values of Ω_{0m}, $w(z)$ is closer to the ΛCDM accepted value $w = -1$.

Unfortunately there is still two problems with GRBs data: the uncertainties and the few data samples that do not allow us to obtain definite conclusions. However the situation is quite likely to change as more and better quality GRB measurements are expected to become available in the near future.

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