

Dark-Energy Equation-of-State parameter for high redshifts.

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Abstract. Since the elucidation of the nature of dark energy depends strongly on redshift observations, it is desirable to measure them over a wider range, but supernovae cannot be detected out past redshift 1.7. Gamma-ray-bursts (GRBs) offer means to extend the analysis to at least redshifts of > 6 . The reason is that GRBs are visible across much larger distances than supernovae. GRBs are now known to have several light-curve and spectral properties from which the luminosity of the burst can be calculated, and it might GRBs become into standard candles. We have used data of 69 GRB to study the behavior of the parameter of the dark energy equation of state as a function of redshift.

1. Introduction

Nowadays cosmological models can be confronted with real data. The observed cosmic microwave background (CMB) with a temperature of around 2.73 K with tiny temperature differences of about 10^{-5} between the different patches of the sky, sustains the assumption of homogeneity of the universe, at a certain scale. Moreover, in 1998, very refined observations of the brightness of distant supernovae seemed to hint the presence of a negative pressure component in the universe, which would make it to expand acceleratedly. In other words, some distant supernovae were fainter than expected and the most compelling explanation was that their light had travelled greater distances than assumed. To fit with the observed behaviour of supernovae redshifts, the cause of the accelerated expansion, the so called dark energy, should exert a negative pressure.

Therefore the more accurate knowledge of the dark-energy Equation of State (EoS) is of paramount importance to understand its nature: if it evolves with time, how much of it is there or if it is rather a manifestation of extra-dimensional physics. By making observations of distances over a wide range of redshifts we can place significant constraints on models of the universe. So a strong imperative in the quest for dark energy is to extend the analysis to high redshifts. However the range of observed redshifts of the supernovae is $0.1 < z < 1.7$. On the other hand, Gamma-ray bursts (GRB) are visible across much larger distances than supernovae, then GRBs offer the chance to extend the Hubble diagram (the plot of distance versus redshift) to at least redshifts of $z \approx 6$.

In this contribution we explore the dependence of the parameter $w(z)$ of the dark-energy (DE) equation-of-state ($p = w(z)\rho$), on the redshift derived from GRBs data. To this end we first find a reasonable calibration for the GRB in order to extract the luminosity distance d_L

as a function of the redshift. Then we proceed to calculate the Hubble function $H(z)$ to obtain $w(z)$. In the next section we briefly summarize the main features of the cosmological model.

2. The model with FRW spacetime

As we mention above, the homogeneity of the universe, to a certain scale, is strongly suggested by the uniformity of the observed CMB, with anisotropies of about 10^{-5} . This makes suitable to model the universe with a homogeneous and isotropic geometry, like the Friedmann-Robertson-Walker (FRW). It combined with the assumption that general relativity is the correct theory on cosmological scales leads to the Friedmann equations for the scale function $a(t)$, that governs the expansion of the universe.

General Relativity is the theory that models the gravitational interaction with the spacetime curvature, this quoted in the Einstein Eqs. $R_{\mu\nu} + Rg_{\mu\nu}/2 = 8\pi T_{\mu\nu}$. The right hand side of this equation is the energy-momentum tensor $T_{\mu\nu}$, that includes the matter content of the universe, that is assumed to be a perfect fluid, whose equation of state is put by hand. This perfect fluid is the contribution of several components among them: barionic matter and dark matter (the curvature component is assumed to vanish, according to the observations). The left hand side of the Einstein equations is related to the curvature quantities, that are derived from the assumed FRW geometry. From these assumptions the derived Friedmann equations are

$$H^2(a) = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho(a), \quad k = 0, \quad (1)$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p), \quad (2)$$

where $a(t)$ is the scale factor of the universe, a dimensionless quantity customarily chosen to be 1 at present; ρ is its average energy density and $H(a)$ is the Hubble parameter or the rate of expansion of the universe.

Both sides of the first Friedmann equation can be observationally probed directly. To fit with the supernovae redshift observations Eq. (1), demands another component besides the dust that models barionic matter, $\rho(a) = \rho_m(a) \sim a^{-3}$ even if a non-zero curvature is assumed. One possible resolution to this puzzle is to modify the right hand side of the Friedmann equation, Eq. (1), by introducing a new form of “dark” energy component, $\rho(a) = \rho_m(a) + \rho_X(a)$.

Before going on, we define the fractional density parameter as

$$\Omega_i = \frac{\rho_i}{\rho_{ic}} = \frac{8\pi G\rho_i}{3H^2}, \quad (3)$$

where ρ_{ic} is the critical density for which the spatial geometry is flat. The density in Eq. (3) is the fractional density for the i -component of the universe. The several components, tagged as ρ_i , mainly are the gravitational matter and the dark energy densities. Observations point to the flatness of the universe, i.e. $\Omega_{\text{total}} = \sum \Omega_i = 1$ (assuming zero curvature). The fact that the sum of densities is equal to one is called the *concordance model*, that can also be expressed as $\Omega_\Lambda + \Omega_m = 1$, where Ω_Λ and Ω_m are the critical density of dark energy and of gravitational matter, respectively; the latter includes dark matter and barionic matter.

3. $\omega(z)$ Parameter of the EoS from observations

The required gravitational properties of dark energy needed to induce the accelerated expansion are well described by its equation of state

$$\omega(z) = \frac{p_X(z)}{\rho_X(z)}, \quad (4)$$

which enters into the second Friedmann equation Eq. (2), implying that a negative pressure ($\omega < -1/3$) is necessary in order to induce accelerated expansion.

The parameter $\omega(z)$ determines not only the gravitational properties of dark energy but also its evolution. This evolution is easily obtained from the energy momentum conservation

$$d(\rho_X a^3) = -p_X d(a^3), \quad (5)$$

which leads to

$$\rho_X = \rho_{0X} e^{3 \int_0^z \frac{dz'}{1+z'} (1+\omega(z'))}, \quad (6)$$

where the subscript '0' indicates the present value of the quantity. From Eq. (6) we see that the determination of $\omega(z)$ is equivalent to that of $\rho_X(z)$ which in turn is related to the Hubble parameter $H(z)$, that from the first Friedmann equation and using (6) can be expressed as

$$H(z)^2 = H_0(z)^2 [\Omega_{0m}(1+z)^3 + \Omega_{0X} e^{3 \int_0^z \frac{dz'}{1+z'} (1+\omega(z'))}]. \quad (7)$$

Thus, the knowledge of Ω_{0m} , z and $H(z)$ suffices to determine $\omega(z)$ which is obtained from the previous equation as

$$\omega(z) = \frac{\frac{2}{3}(1+z) \frac{d \ln H}{dz} - 1}{1 - \frac{H_0^2}{H^2} \Omega_{0m} (1+z)^3}. \quad (8)$$

From observational data it is possible to extract $d_L(z)$ and then determine $H(z)$, since,

$$H(z) = \left\{ \frac{d}{dz} \left(\frac{d_L(z)}{1+z} \right) \right\}^{-1}. \quad (9)$$

So the main quantity to find is the luminosity distance d_L as a function of the redshift z of distant objects. Measuring redshifts is straightforward from the detected spectrum of the luminous object; the hard part is determining distances for objects of unknown intrinsic brightness. One of the most popular techniques is to try to find a standard candle. Standard candles are objects in the universe with a well calibrated intrinsic luminosity that can be used to determine distances on cosmological scales. Type Ia supernovae are these kind of objects [1], 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.

Therefore, 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.

4. Calibrating Gamma-ray burst.

There are several distance indicators to determine the cosmological luminosity distance $d_L(z)$. If a certain distance indicator is calibrated without any cosmological model, the indicator can be used to determine the cosmological parameters such as Ω_m , Ω_Λ and $\omega = p/\rho$.

In this section we show a calibration for a 69 GRBs sample [2], where the luminosity distance is a function of the redshift for two intervals, $z \leq 1.755$ and $z > 1.755$. Based in the data of Type Ia Supernovae, the calibration obtained by Kodama et al.[3] was,

$$\frac{d_L(z)}{10^{27} cm} = 14.57z^{1.02} + 7.16z^{1.76}. \quad (10)$$

With Eq. (10) and the 69 GRBs observational data, we can use Eq. (9) and in this way infer if the dark energy effective EoS parameter ω is close to -1 (cosmological constant). Any small deviation from this value could give a different theoretical scenario: if it is exactly equal (when

of course referring to observational errors) to -1, we have a cosmological constant; if it is larger than -1, we have quintessence energy; while if it is smaller than -1 we have the so called phantom dark energy.

However with the Kodama calibration we obtained a plot for $w(z)$ that was physically unreasonable, diverging at certain redshift. This was not reported in [3].

We tried to repair this inconsistency by finding out another calibration for the GRBs extracted directly from data. In order to calibrate the GRB observed data and obtain the dependence rule between the luminosity distance d_L and the redshift z , we try the five possible relationships proposed in [2].

These relate GRBs isotropic luminosity, L , or the total burst energy in the gamma rays, E_γ , to the observables of the light curves and/or spectra: τ_{lag} , the time lag, V variability, the peak of the νF_ν spectrum E_{peak} and τ_{RT} , the minimum rise time, as follows,

$$\log\left(\frac{L}{1\text{ergs}^{-1}}\right) = 52.26 - 1.01\log\left[\frac{\tau_{lag}(1+z)^{-1}}{0.1s}\right], \quad (11)$$

$$\log\left(\frac{L}{1\text{ergs}^{-1}}\right) = 52.49 + 1.77\log\left[\frac{V(1+z)}{0.02}\right], \quad (12)$$

$$\log\left(\frac{L}{1\text{ergs}^{-1}}\right) = 52.21 + 1.68\log\left[\frac{E_{peak}(1+z)}{300\text{keV}}\right], \quad (13)$$

$$\log\left(\frac{E_\gamma}{1\text{ergs}^{-1}}\right) = 52.57 + 1.63\log\left[\frac{E_{peak}(1+z)}{300\text{keV}}\right], \quad (14)$$

$$\log\left(\frac{L}{1\text{ergs}^{-1}}\right) = 52.54 - 1.21\log\left[\frac{\tau_{RT}(1+z)^{-1}}{0.1s}\right]. \quad (15)$$

The isotropic luminosity L is given by

$$L = 4\pi d_L^2 P_{bolo}, \quad (16)$$

where P_{bolo} is a observational quantity reported in [2].

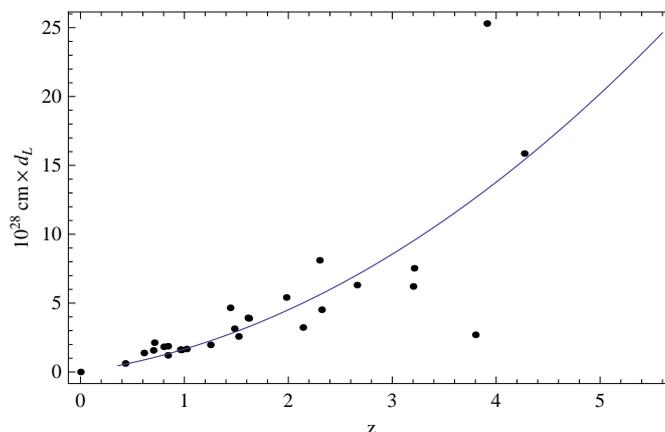


Figure 1. The luminosity distance as a function of the redshift of GRBs, Eq. (18) derived using the calibrated $E_\gamma - E_{peak}$ relation.

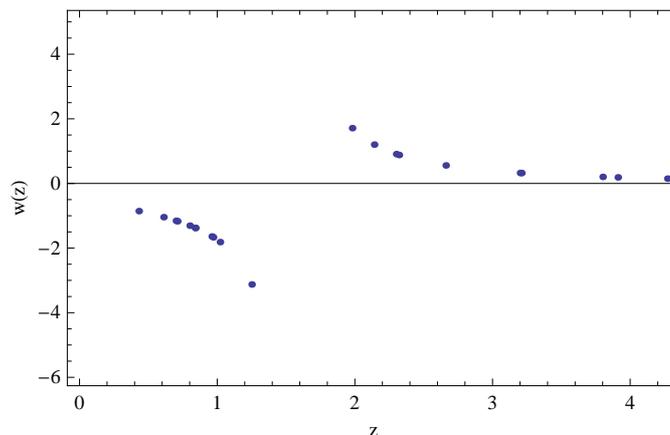


Figure 2. $w(z)$ parameter of the equation of state as a function of z , derived from 26 subset of GRBs given in [2].

The plot between E_γ vs E_{peak} , Eq. (14), turned out to be the best to find a tendency. To obtain $d_L(z)$ from this calibration one has the relation

$$d_L^2 = \frac{(1+z)}{4\pi S_{\text{bolo}} F_{\text{beam}}} 10^{\left[50.57 + 1.63 \log\left(\frac{E_{\text{peak}}}{300 \text{ keV}} (1+z)\right)\right]} \text{cm}^2, \quad (17)$$

where S_{bolo} and F_{beam} are observationally reported in [2].

The adjust of the data gives the following rule, see Fig. (1),

$$\frac{d_L(z)}{10^{27} \text{cm}} = 10.7z + 5.9z^2, \quad (18)$$

that is not far from the one proposed in [3], Eq. 10. We note that this calibration was obtained for a 26 subset of 69 GRBs data.

Using this extracted rule for the luminosity distance as function of z and using Eq. (8), we derived the dark-energy equation-of-state parameter $w(z)$, Fig. (2).

The plot of $w(z)$ is not continuous, but shows a divergence at certain z around 1.54. The reason of this divergence is that Eq. (8) blows up when $H^2(z) = H_0^2 \Omega_{0m} (1+z)^3$, then Eq. (8) does not work for all the range of z , unless we consider values of Ω_{0m} smaller than ordinarily accepted. In other words, larger redshifts demand more abundance of dark energy and consequently less gravitational matter due to the concordance model. Our results point to the need of an alternative way to determine $w(z)$ appropriate to large redshifts.

5. Conclusions

The aim of this work is to determine the functional dependence of the dark-energy equation-of-state parameter in terms of the redshift, $w(z)$, from observational data coming from the GRBs. First we find the best calibration between the observational data of GRBs, obtaining the luminosity distance as function of redshift, $d_L(z)$, Eq. (18). Then we obtain the corresponding Hubble function and then $w(z)$. However we found an anomalous behavior in $w(z)$. The reason is an inconsistency of $w(z)$, Eq. (8), that has a limited range of validity, that we found to be for $z < 1.54$.

During the process of this research we learned of similar works, for instance [4], where the EoS is adopted and then tested. We remark that in our work we tried to extract $w(z)$ directly from data only assuming the FRW and concordance model.

With the improving of the observations, in particular with the recent launch of new satellites devoted to GRBs surveys, as Fermi-GLAST and AGILE, one should be able to expand the samples of GRBs and this will allow more robust analysis for $w(z)$ using GRBs.

Acknowledgments

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References

- [1] S. Dodelson 2003 *Modern Cosmology* (USA: Academic Press)
- [2] B. E. Schaefer 2007 *Astrophys. J.* **660** 16
- [3] Y. Kodama et. al. 2008 *Mon. Not. R. Astron. Soc.* **391** L1-L4
- [4] S. Capozziello, L. Izzo 2009 *Nuclear Physics B* **194** 206-211