Cosmological Models and Latest Observational Data

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ABSTRACT

In this note, we consider the observational constraints on some cosmological models by using the 307 Union type Ia supernovae (SNIa), the 32 calibrated Gamma-Ray Bursts (GRBs) at $z > 1.4$, the updated shift parameter $R$ from WMAP 5-year data (WMAP5), and the distance parameter $A$ of the measurement of the baryon acoustic oscillation (BAO) peak in the distribution of SDSS luminous red galaxies with the updated scalar spectral index $n_s$ from WMAP5. The tighter constraints obtained here update the ones obtained previously in the literature.

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I. INTRODUCTION

Recently, some observational data have been updated or have become available. In \[1,2\], the Wilkinson Microwave Anisotropy Probe (WMAP) collaboration released their 5-year observational data (WMAP5). The data of Cosmic Microwave Background (CMB) anisotropy have been significantly improved. Also, in \[3,4\], the Supernova Cosmology Project (SCP) collaboration released their new dataset of type Ia supernovae (SNIa), which was called the Union compilation. The Union compilation contains 414 SNIa and reduces to 307 SNIa after selection cuts. This 307 SNIa Union compilation is the currently largest SNIa dataset.

On the other hand, Gamma-Ray Bursts (GRBs) were proposed as a complementary probe to SNIa recently \[5,6\]. GRBs have been advocated as standard candles since several empirical GRB luminosity relations were proposed as distance indicators. However, there is the so-called circularity problem in the direct use of GRBs to probe cosmology \[5\]. Recently, a new idea to calibrate GRBs in a completely cosmology independent manner has been proposed \[9,10\], and the circularity problem can be solved. The main idea is that of the cosmic distance ladder. Similar to the case of calibrating SNIa as the secondary standard candles by using Cepheid variables, which are primary standard candles, we can also calibrate GRBs as standard candles with a large amount of SNIa. Following the calibration method proposed in \[10\], the distance moduli \( \mu \) of 32 calibrated GRBs at redshift \( z > 1.4 \) are derived in \[11\]. Now, one can use them to constrain cosmological models without circularity problem. See \[10,11\] for details. As argued in \[8,32\], the observations at \( z > 1.7 \) are fairly important to distinguish cosmological models and break the degeneracies between the parameters. In this note, we try to combine GRBs with the conventional datasets to constrain cosmological models. Although the number of GRBs is small and the systematic and statistical errors are very large so that their contribution to the constraints would be not so significant, this is still a beneficial exploration.

Here, we consider the observational constraints on some cosmological models by using the 307 Union SNIa compiled in \[3\], the 32 calibrated GRBs at \( z > 1.4 \) compiled in Table I of \[11\], the updated shift parameter \( R \) from WMAP5 \[1\], and the distance parameter \( A \) of the measurement of the baryon acoustic oscillation (BAO) peak in the distribution of SDSS luminous red galaxies \[12\] with the updated scalar spectral index \( n_s \) from WMAP5 \[1\].

We perform a \( \chi^2 \) analysis to obtain the constraints on the parameters of cosmological models. The data points of the 307 Union SNIa compiled in \[3\] and the 32 calibrated GRBs at \( z > 1.4 \) compiled in Table I of \[11\] are given in terms of the distance modulus \( \mu_{\text{obs}}(z_i) \). On the other hand, the theoretical distance modulus is defined as

\[
\mu_{\text{th}}(z_i) = 5 \log_{10} D_L(z_i) + \mu_0,
\]

where \( \mu_0 = 42.38 - 5 \log_{10} h \) and \( h \) is the Hubble constant \( H_0 \) in units of 100 km/s/Mpc, whereas

\[
D_L(z) = (1 + z) \int_0^z \frac{d\tilde{z}}{E(\tilde{z}; p)},
\]

in which \( E \equiv H/H_0 \) and \( H \) is the Hubble parameter; \( p \) denotes the model parameters. The \( \chi^2 \) from the 307 Union SNIa and the 32 calibrated GRBs at \( z > 1.4 \) are given by

\[
\chi^2(p) = \sum_i \frac{[\mu_{\text{obs}}(z_i) - \mu_{\text{th}}(z_i)]^2}{\sigma^2_{\mu_{\text{obs}}}(z_i)}.
\]

where \( \sigma \) is the corresponding 1\( \sigma \) error. The parameter \( \mu_0 \) is a nuisance parameter but it is independent of the data points. One can perform an uniform marginalization over \( \mu_0 \). However, there is an alternative way. Following \[13,14\], the minimization with respect to \( \mu_0 \) can be made by expanding the \( \chi^2_{\mu} \) of Eq. (3) with respect to \( \mu_0 \) as

\[
\chi^2_{\mu}(p) = \tilde{A} - 2\mu_0 \tilde{B} + \mu_0^2 \tilde{C},
\]

where

\[
\tilde{A}(p) = \sum_i \frac{[\mu_{\text{obs}}(z_i) - \mu_{\text{th}}(z_i; \mu_0 = 0, p)]^2}{\sigma^2_{\mu_{\text{obs}}}(z_i)},
\]

\[
\tilde{B}(p) = \sum_i \frac{[\mu_{\text{obs}}(z_i) - \mu_{\text{th}}(z_i; \mu_0 = 0, p)]}{\sigma_{\mu_{\text{obs}}}(z_i)} \frac{d\mu_{\text{th}}(z_i; \mu_0 = 0, p)}{d\mu_0},
\]

\[
\tilde{C}(p) = \frac{1}{2} \left( \sum_i \frac{d\mu_{\text{th}}(z_i; \mu_0 = 0, p)}{d\mu_0} \right)^2.
\]
\[
\hat{B}(p) = \sum_i \frac{\mu_{obs}(z_i) - \mu_{th}(z_i; \mu_0 = 0, p)}{\sigma_{\mu_{obs}}^2(z_i)}, \quad \hat{C} = \sum_i \frac{1}{\sigma_{\mu_{obs}}^2(z_i)}.
\]

Eq. (4) has a minimum for \(\mu_0 = \hat{B}/\hat{C}\) at

\[\chi^2_\mu(p) = A(p) - \frac{\hat{B}(p)^2}{\hat{C}}.\] (5)

Since \(\chi^2_{\mu, min} = \chi^2_{\mu, min}\) obviously, we can instead minimize \(\chi^2\) which is independent of \(\mu_0\). Note that the above summations are over the 307 Union SNIa compiled in [3] and the 32 calibrated GRBs at \(z > 1.4\) compiled in Table I of [11]. On the other hand, the shift parameter \(R\) is defined by [13, 16]

\[R \equiv \Omega_{m0}^{1/2} \int_{z^*}^{z_b} \frac{d\tilde{z}}{E(\tilde{z})},\] (6)

where the redshift of recombination \(z_\ast = 1090\) which has been updated in [1], and \(\Omega_{m0}\) is the present fractional energy density of pressureless matter. The shift parameter \(R\) relates the angular diameter distance to the last scattering surface, the comoving size of the sound horizon at \(z_\ast\) and the angular scale of the first acoustic peak in the CMB power spectrum of the temperature fluctuations [12, 16]. The value of \(R\) has been updated to \(1.710 \pm 0.019\) from WMAP5 [1]. The distance parameter \(A\) is given by

\[A \equiv \Omega_{m0}^{1/2} E(z_b)^{-1/3} \left[ \frac{1}{z_b} \int_0^{z_b} \frac{d\tilde{z}}{E(\tilde{z})} \right]^{2/3},\] (7)

where \(z_b = 0.35\). In [17], the value of \(A\) has been determined to be \(0.469 (n_s/0.98)^{-0.35} \pm 0.017\). Here the scalar spectral index \(n_s\) is taken to be 0.960 which has been updated from WMAP5 [1]. So, the total \(\chi^2\) is given by

\[\chi^2 = \chi^2_{\mu} + \chi^2_{CMB} + \chi^2_{BAO}.\] (8)

where \(\chi^2_{\mu}\) is given in Eq. (5), \(\chi^2_{CMB} = (R - R_{obs})^2/\sigma_R^2\) and \(\chi^2_{BAO} = (A - A_{obs})^2/\sigma_A^2\). The best-fit model parameters are determined by minimizing the total \(\chi^2\). As in [18], the 68% confidence level is determined by \(\Delta \chi^2 \equiv \chi^2 - \chi^2_{\mu, min} \leq 1.0, 2.3\) and 3.53 for \(n_p = 1, 2\) and 3, respectively, where \(n_p\) is the number of free model parameters. Similarly, the 95% confidence level is determined by \(\Delta \chi^2 \equiv \chi^2 - \chi^2_{\mu, min} \leq 4.0, 6.17\) and 8.02 for \(n_p = 1, 2\) and 3, respectively.

In sections [II, III and IV] we consider the joint constraints on single-parameter, two-parameter and three-parameter cosmological models respectively, by using the 307 Union SNIa compiled in [3], the 32 calibrated GRBs at \(z > 1.4\) compiled in Table I of [11], the updated shift parameter \(R\) from WMAP5 [1], and the distance parameter \(A\) of the measurement of BAO peak in the distribution of SDSS luminous red galaxies [12] with the updated scalar spectral index \(n_s\) from WMAP5 [1]. Note that we also present the constraints without GRBs for comparison. A brief summary is given in section [V].

II. SINGLE-PARAMETER MODELS

In this section, we consider the constraints on three single-parameter models. They are the flat \(\Lambda\)CDM model, the flat DGP model and the new agegraphic dark energy (NADE) model.

A. Flat \(\Lambda\)CDM model

As is well known, for the spatially flat \(\Lambda\)CDM model,

\[E(z) = \sqrt{\Omega_{m0}(1+z)^3 + (1 - \Omega_{m0})}.\] (9)
It is easy to obtain the total $\chi^2$ as a function of the single model parameter $\Omega_{m0}$. In Fig. 1, we present the corresponding likelihood $L \propto e^{-\chi^2/2}$. The best fit has $\chi^2_{\text{min}} = 325.522$, whereas the best-fit parameter is $\Omega_{m0} = 0.2714^{+0.0159}_{-0.0152}$ (with $1\sigma$ uncertainty) or $\Omega_{m0} = 0.2714^{+0.0324}_{-0.0297}$ (with $2\sigma$ uncertainty).

For comparison, we also present the likelihood without GRBs in Fig. 1 whereas the best-fit parameter reads $\Omega_{m0} = 0.2698^{+0.0159}_{-0.0152}$ (with $1\sigma$ uncertainty) or $\Omega_{m0} = 0.2698^{+0.0324}_{-0.0297}$ (with $2\sigma$ uncertainty).

**B. Flat DGP model**

One of the leading modified gravity models is the so-called Dvali-Gabadadze-Porrati (DGP) braneworld model [19, 20], which entails altering the Einstein-Hilbert action by a term arising from large extra dimensions. For a list of references on the DGP model, see e.g. [21, 22] and references therein.

As is well known, for the spatially flat DGP model (here we only consider the self-accelerating branch), $E(z)$ is given by [20, 21, 22]

$$E(z) = \sqrt{\Omega_{m0}(1+z)^3 + \Omega_{r_c} + \sqrt{\Omega_{r_c}}} \, ,$$

(10)

where $\Omega_{r_c}$ is constant. $E(z = 0) = 1$ requires

$$\Omega_{m0} = 1 - 2\sqrt{\Omega_{r_c}} \, .$$

(11)

Therefore, the flat DGP model has only one independent model parameter. Notice that $0 \leq \Omega_{r_c} \leq 1/4$ is required by $0 \leq \Omega_{m0} \leq 1$.

It is easy to obtain the total $\chi^2$ as a function of the single model parameter $\Omega_{r_c}$. Also in Fig. 1 we plot the corresponding likelihood $L \propto e^{-\chi^2/2}$. The best fit has $\chi^2_{\text{min}} = 345.56$, whereas the best-fit parameter is $\Omega_{r_c} = 0.1286^{+0.0056}_{-0.0057}$ (with $1\sigma$ uncertainty) or $\Omega_{r_c} = 0.1286^{+0.0111}_{-0.0116}$ (with $2\sigma$ uncertainty). From Eq. (11), $\Omega_{m0}$ can be derived correspondingly.

For comparison, we also present the likelihood without GRBs in Fig. 1 whereas the best-fit parameter reads $\Omega_{r_c} = 0.1289^{+0.0056}_{-0.0057}$ (with $1\sigma$ uncertainty) or $\Omega_{r_c} = 0.1289^{+0.0111}_{-0.0116}$ (with $2\sigma$ uncertainty).
C. New agegraphic dark energy model

In [23, 24], the so-called “new agegraphic dark energy” (NADE) model has been proposed recently, based on the Károlyházy uncertainty relation which arises from quantum mechanics together with general relativity. In this model, the energy density of NADE is given by [23, 24]

\[ \rho_q = \frac{3n^2 m_p^2}{\eta^2}, \]

where \( m_p \) is the reduced Planck mass; \( n \) is a constant of order unity; \( \eta \) is the conformal time

\[ \eta \equiv \int \frac{dt}{a} = \int \frac{da}{a^2 H}, \]

in which \( a = (1 + z)^{-1} \) is the scale factor. Obviously, \( \dot{\eta} = 1/a \), where a dot denotes the derivative with respect to cosmic time \( t \). The corresponding fractional energy density of NADE reads

\[ \Omega_q = \frac{\rho_q}{3m_p^2 H^2} = \frac{n^2}{H^2 \eta^2}. \]

From the Friedmann equation \( H^2 = (\rho_m + \rho_q)/(3m_p^2) \), the energy conservation equation \( \dot{\rho}_m + 3H \rho_m = 0 \), and Eqs. (12) – (14), we find that the equation of motion for \( \Omega_q \) is given by [23, 24]

\[ \frac{d\Omega_q}{dz} = -\Omega_q (1 - \Omega_q) \left[ 3(1 + z)^{-1} - \frac{2}{n} \sqrt{\Omega_q} \right]. \]

From the energy conservation equation \( \dot{\rho}_q + 3H (\rho_q + p_q) = 0 \), and Eqs. (12) – (14), it is easy to find that the equation-of-state parameter (EoS) of NADE is given by [23, 24]

\[ w_q \equiv \frac{p_q}{\rho_q} = -1 + \frac{2}{3n} \frac{\sqrt{\Omega_q}}{a}. \]

When \( a \to \infty \), \( \Omega_q \to 1 \), thus \( w_q \to -1 \) in the late time. When \( a \to 0 \), \( \Omega_q \to 0 \), so \( 0/0 \) appears in \( w_q \) and hence we cannot obtain \( w_q \) from Eq. (16) directly. Let us consider the matter-dominated epoch, \( H^2 \propto \rho_m \propto a^{-3} \). Thus, \( a^{1/2} da \propto dt = a d\eta \). Therefore, \( \rho_m \propto a^{-1} \). From the energy conservation equation \( \dot{\rho}_m + 3H \rho_m (1 + w_q) = 0 \), we obtain \( w_q = -2/3 \) in the matter-dominated epoch. Since \( \rho_m \propto a^{-3} \) and \( \rho_q \propto a^{-1} \), it is expected that \( \Omega_q \propto a^2 \). Comparing \( w_q = -2/3 \) with Eq. (16), we find that \( \Omega_q = n^2 a^2/4 \) in the matter-dominated epoch as expected. For \( a \ll 1 \), provided that \( n \) is of order unity, \( \Omega_q \ll 1 \) naturally follows. There are many interesting features in the NADE model and we refer to the original papers [23, 24] for more details.

At first glance, one might consider that NADE is a two-parameter model. However, as shown in [23], NADE is a single-parameter model in practice, thanks to its special analytic feature \( \Omega_q = n^2 a^2/4 = n^2 (1 + z)^{-2}/4 \) in the matter-dominated epoch, as mentioned above. If \( n \) is given, we can obtain \( \Omega_q(z) \) from Eq. (14) with the initial condition \( \Omega_q(z_{ini}) = n^2(1 + z_{ini})^{-2}/4 \) at any \( z_{ini} \) which is deep enough into the matter-dominated epoch (we choose \( z_{ini} = 2000 \) as in [23]), instead of \( \Omega_q(z = 0) = \Omega_{q0} = 1 - \Omega_{m0} \) at \( z = 0 \). Then, all other physical quantities, such as \( \Omega_m(z) = 1 - \Omega_q(z) \) and \( w_m(z) \) in Eq. (16), can be obtained correspondingly. So, \( \Omega_{m0} = \Omega_m(z = 0), \Omega_{q0} = \Omega_q(z = 0) \) and \( w_{q0} = w_q(z = 0) \) are not independent model parameters. The only model parameter is \( n \). Therefore, the NADE model is a single-parameter model in practice. To our knowledge, it is the third single-parameter cosmological model besides the flat ΛCDM model and the flat DGP model.

From the Friedmann equation \( H^2 = (\rho_m + \rho_q)/(3m_p^2) \), we have

\[ E(z) = \left[ \frac{\Omega_{m0}(1 + z)^3}{1 - \Omega_q(z)} \right]^{1/2}. \]

If the single model parameter \( n \) is given, we can obtain \( \Omega_q(z) \) from Eq. (15). Thus, we get \( \Omega_{m0} = 1 - \Omega_q(z = 0) \). So, \( E(z) \) is at hand. Therefore, we can find the corresponding total \( \chi^2 \) in Eq. (8). In Fig. 2
we plot the corresponding likelihood $\mathcal{L} \propto e^{-\chi^2/2}$ as a function of $n$. The best fit has $\chi^2_{\text{min}} = 336.061$, whereas the best-fit parameter is $n = 2.802$. We present the best-fit value of $n$ and the corresponding derived $\Omega_{m0}$, $\Omega_{q0}$ and $w_{q0}$ with 1$\sigma$ and 2$\sigma$ uncertainties in Table I. Obviously, these constraints on the NADE model are tighter than the ones obtained in [23].

For the case without GRBs, the best-fit parameter is $n = 2.808$. For comparison, we also present the best-fit value of $n$ and the corresponding derived $\Omega_{m0}$, $\Omega_{q0}$ and $w_{q0}$ with 1$\sigma$ and 2$\sigma$ uncertainties in Table I.

| Uncertainty       | $n$              | $\Omega_{m0}$ | $\Omega_{q0}$ | $w_{q0}$     |
|-------------------|------------------|----------------|----------------|--------------|
| 1$\sigma$ (with GRBs) | $2.802^{+0.092}_{-0.090}$ | $0.279^{+0.016}_{-0.015}$ | $0.721^{+0.015}_{-0.016}$ | $-0.798^{+0.004}_{-0.004}$ |
| 2$\sigma$ (with GRBs) | $2.802^{+0.185}_{-0.179}$ | $0.279^{+0.033}_{-0.030}$ | $0.721^{+0.030}_{-0.033}$ | $-0.798^{+0.009}_{-0.009}$ |
| 1$\sigma$ (without GRBs) | $2.808^{+0.092}_{-0.090}$ | $0.278^{+0.016}_{-0.015}$ | $0.722^{+0.015}_{-0.016}$ | $-0.798^{+0.004}_{-0.004}$ |
| 2$\sigma$ (without GRBs) | $2.808^{+0.186}_{-0.179}$ | $0.278^{+0.033}_{-0.030}$ | $0.722^{+0.030}_{-0.033}$ | $-0.798^{+0.009}_{-0.009}$ |

TABLE I: The best-fit value of $n$ and the corresponding derived $\Omega_{m0}$, $\Omega_{q0}$ and $w_{q0}$ with 1$\sigma$ and 2$\sigma$ uncertainties for the NADE model. See text for details.

![FIG. 2: The likelihood $\mathcal{L} \propto e^{-\chi^2/2}$ for the NADE model. The results for the cases with and without GRBs are indicated by the black solid line and the red dashed line, respectively.](image)

**III. TWO-PARAMETER MODEL**

Here, we consider the XCDM model which is a two-parameter model. In the spatially flat universe which contains pressureless matter and dark energy whose EoS is a constant $w$, the corresponding $E(z)$ is given by

$$E(z) = \sqrt{\Omega_{m0}(1+z)^3 + (1-\Omega_{m0})(1+z)^3(1+w)}.$$  

(18)
By minimizing the corresponding total $\chi^2$ in Eq. (8), we find the best-fit parameters $\Omega_{m0} = 0.271$ and $w = -0.951$, while $\chi^2_{\text{min}} = 324.821$. In Fig. 3 we present the corresponding 68% and 95% confidence level contours in the $\Omega_{m0} - w$ parameter space for the XCDM model. For comparison, the best-fit parameters are $\Omega_{m0} = 0.270$ and $w = -0.954$ for the case without GRBs, whereas the corresponding confidence level contours are also presented in Fig. 3.

![Diagram](image)

**FIG. 3:** The 68% and 95% confidence level contours in the $\Omega_{m0} - w$ parameter space for the XCDM model. The results for the cases with and without GRBs are indicated by the black solid lines and the red dashed lines, respectively. The best-fit parameters for the cases with and without GRBs are also indicated by a black solid point and a red box, respectively.

### IV. THREE-PARAMETER MODEL

Now, we consider the familiar Chevallier-Polarski-Linder (CPL) model \[25, 26\], in which the EoS of dark energy is parameterized as

$$w_{de} = w_0 + w_a(1 - a) = w_0 + w_a \frac{z}{1 + z},$$

where $w_0$ and $w_a$ are constants. As is well known, the corresponding $E(z)$ is given by \[18, 27, 28\]

$$E(z) = \left[ \Omega_{m0}(1 + z)^3 + (1 - \Omega_{m0})(1 + z)^{3(1 + w_0 + w_a)} \exp \left( -\frac{3w_a z}{1 + z} \right) \right]^{1/2}.\tag{20}$$

There are 3 independent parameters in this model. By minimizing the corresponding total $\chi^2$ in Eq. (8), we find the best-fit parameters $\Omega_{m0} = 0.280$, $w_0 = -1.146$ and $w_a = 0.894$, while $\chi^2_{\text{min}} = 322.475$. In Fig. 4 we present the corresponding 68% and 95% confidence level contours in the $w_0 - w_a$ plane for the CPL model. Also, the 68% and 95% confidence level contours in the $\Omega_{m0} - w_0$ plane and the $\Omega_{m0} - w_a$ plane for the CPL model are shown in Fig. 5. It is easy to see that these constraints on the CPL model are much tighter than the ones obtained in \[29\].

For comparison, the best-fit parameters are $\Omega_{m0} = 0.278$, $w_0 = -1.140$ and $w_a = 0.859$ for the case without GRBs, whereas the corresponding confidence level contours are also presented in Figs. 4 and 5.
V. SUMMARY

In this note, we consider the observational constraints on some cosmological models by using the 307 Union SNIa compiled in [3], the 32 calibrated GRBs at $z > 1.4$ compiled in Table I of [11], the updated shift parameter $R$ from WMAP5 [1], and the distance parameter $A$ of the measurement of the baryon acoustic oscillation (BAO) peak in the distribution of SDSS luminous red galaxies [12] with the updated scalar spectral index $n_s$ from WMAP5 [1]. The tighter constraints obtained here update the ones obtained previously in the literature (e.g. [13, 14, 18, 23, 28, 29, 30, 31]).

It is worth noting that GRBs are potential tools which might be powerful to probe the cosmic expansion history up to $z > 6$ or even higher redshift. Of course, due to the large scatter and the lack of a large amount of well observed GRBs, there is a long way to go in using GRBs extensively and reliably to probe cosmology. The cosmology independent calibration method of GRBs proposed in [10] is an important step towards this end. The works of this note and [11] are beneficial explorations. Along with the accumulation of well observed GRBs with much smaller errors, we believe that a bright future of GRB cosmology is awaiting us. Combining the calibrated GRBs with other probes such as SNIa, CMB, large-scale structure and weak lensing, we can learn more about the mysterious dark energy.

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FIG. 5: The same as in Fig. 4 except for the $\Omega_{m0} - w_0$ plane and the $\Omega_{m0} - w_a$ plane.

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