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Constraints on cosmic distance duality relation from cosmological observations

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ABSTRACT

In this paper, we use the model dependent method to revisit the constraint on the well-known cosmic distance duality relation (CDDR). By using the latest SNIa samples, such as Union2.1, JLA and SNLS, we find that the SNIa data alone cannot constrain the cosmic opacity parameter ε, which denotes the deviation from the CDDR, $d_L = d_A(1+z)^{2+\varepsilon}$, very well. The constraining power on ε from the luminosity distance indicator provided by SNIa and GRB is hardly to be improved at present. When we include other cosmological observations, such as the measurements of Hubble parameter, the baryon acoustic oscillations and the distance information from cosmic microwave background, we obtain the tightest constraint on the cosmic opacity parameter ε, namely the 68% C.L. limit: $\varepsilon = 0.023 \pm 0.018$. Furthermore, we also consider the evolution of ε as a function of z using two methods, the parametrization and the principle component analysis, and do not find the evidence for the deviation from zero. Finally, we simulate the future SNIa and Hubble measurements and find the mock data could give very tight constraint on the cosmic opacity ε and verify the CDDR at high significance.

1. Introduction

In 1998 the analyses of the redshift-distance relation of type Ia supernova (SNIa) at low redshift $z < 2$ have demonstrated that the Universe is now undergoing an accelerated phase of expansion [1,2]. Currently, cosmological observations have provided tight constraints on distance measures: the luminosity distance d_L by measuring the SNIa and the angular diameter distance d_A by measuring the baryon acoustic oscillations (BAO), which can be used to constrain different cosmological parameters in various theoretical models [3]. In general, the luminosity distance and the angular diameter distance should satisfy the well-known cosmic distance duality relation (CDDR):

$$d_L = d_A(1+z)^2. \quad (1)$$

This relation, which is also called "Etherington relation" in the literature, holds only for the validity of three fundamental conditions:

- The spacetime is described by a metric theory of gravity;
- Photons travel along unique null geodesics;
- The number of photons is conserved.

Therefore, any departure from these three conditions, such as the deviation from a metric theory of gravity, photons not traveling along null geodesics and the variation of photon number, will reveal the new physics beyond the standard model.

In the literature, in order to test the CDDR, a model-independent method has been widely used in which people use the current datasets of d_L from SNIa or Gamma-Ray Bursts (GRB) measurements and d_A from BAO or X-ray measurements at the same redshift to constrain the parameter $\eta = d_L/d_A(1+z)^2$ (e.g. see Refs. [4–16] and references therein). If η obtained from the d_L and d_A datasets is different from the unity, the CDDR relation is violated. Recently, Ref. [17] used a new compilation of strong lensing system to extract the information of d_A and obtained the constraint on the parameter: $\eta = -0.004^{+0.322}_{-0.210}$ (68% C.L.), together with the "Joint Luminosity Analyses" (JLA) compilation of SNIa [18]. Apparently, this method for testing CDDR is conservative and independent on the underlying cosmological model. However, the big problem is that current observations cannot provide the information of luminosity distance d_L and angular diameter distance d_A for an astronomical target at same time. Therefore, they have to use the information of d_A from the galaxy cluster observations and d_L from the SNIa measurements at

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the similar redshift, which inevitably brings large numerical errors on the determination of η.

On the other hand, there is another model-dependent method to study this relation. The CDDR is in deep connection with the cosmic opacity [19,20]. A variation of photon number during propagation towards us, which could be caused by some simple astrophysical effects, like the interstellar dust, gas and/or plasmas, and some exotic physics beyond the standard model, will affect the SNIa luminosity distance measures but not the determinations of the angular diameter distance in a certain underlying cosmological framework, and consequently modify the CDDR relation. Assuming $\tau(z)$ denotes the cosmic opacity between an observer at $z = 0$ and a source at z, the flux received from the source would be attenuated by a factor $e^{-\tau(z)}$. Then the luminosity distance has

$$d_{\rm L,obs}(z) = d_{\rm L,true}(z)\exp(\tau(z)/2)\,, \tag{2}$$

because intensity is inversely proportional to square of distance between the source and the observer. Ref. [21] introduced a parameter ε to study deviations from the Etherington relation of the form

$$d_{\rm L}(z) = d_{\rm A}(z)(1+z)^{2+\varepsilon}\,, \tag{3}$$

where ε denotes the departure from the transparency. Considering the small value of ε at low redshift, this is equivalent to assume an optical depth parametrization $\tau(z) = 2\varepsilon z$. The advantage of this method is that we can use the measurements of $d_{\rm L}$ with high precision to constrain the cosmic opacity and avoid to include the large uncertainties from the measurements of galaxy clusters. Currently, the most tight constraint comes from the dataset combination of "Union2 Compilation" SNIa sample and the Hubble parameter as a function of redshift $H(z)$: $\varepsilon = -0.01^{+0.08}_{-0.09}$ (95% C.L.) [22]. Until now, all the measurements satisfy the CDDR relation at 68% confidence level.

In this paper we mainly focus on the model-dependent method to verify the CDDR relation and update the constraints on the cosmic opacity from the latest measurements on SNIa samples of "Union2.1 Compilation" (Union2.1) [23], "Joint Luminosity Analyses" (JLA) [18] and "Supernovae Legacy Survey" (SNLS) [24], as well as the measurement on the Hubble parameter $H(z)$. Furthermore, we also include the GRB, BAO and the distance information of cosmic microwave background (CMB) into the analyses to help improving the constraints on cosmic opacity. The paper is organized as follows: In Section 2, we introduce the datasets used in the analyses. We present the numerical results in Section 3. Finally, in Section 4 conclusion and discussion are drawn.

2. Current datasets

In our calculations, we rely on the following current observational datasets: (i) SNIa and GRB distance moduli; (ii) Hubble parameter determinations; (iii) BAO in the galaxy power spectra; (iv) CMB distance information.

2.1. Type-Ia supernovae & gamma-ray bursts

The SNIa distance moduli provide the luminosity distance as a function of redshift z. In this paper, we use the latest SNIa Union2.1 compilation of 580 dataset from the Hubble Space Telescope Supernova Cosmology Project [23]. The data are usually presented as tabulated distance modulus with errors. In this catalog, the redshift spans $0 < z < 1.414$, and about 95% samples are in the low redshift region $z < 1$. The authors also provided the covariance matrix of data with and without systematic errors. In order to be conservative, we include systematic errors in our calculations.

For comparison, we also consider the following two SNIa data: (1) 472 samples from the first three year of SuperNova Legacy Survey (SNLS) Program (123 low-z, 93 SDSS, 242 SNLS, and 14 Hubble Space Telescope) at $0.01 < z < 1.4$ [24]; (2) 740 samples from the SDSS-II/SNLS3 Joint Light-curve Analysis (JLA) at redshift up to 1.30 including several low-redshift samples ($z < 0.1$), all three seasons from the SDSS-II ($0.05 < z < 0.4$), three years from SNLS ($0.2 < z < 1$) [18].

These two data compilations are different from the Union2.1 in three major aspects: (1) The two supernova nuisance parameters α and β coming from light-curve calibration and are handled correctly instead of held at their best fit values; (2) They offer covariance between the light-curve fit; (3) The luminosity distance takes into account the difference between the CMB frame and heliocentric frame redshifts, which is important for some of the nearby supernova. Furthermore, the JLA compilation includes intrinsic dispersion and gravitational lensing effect in supernova magnitude, while the SNLS does not.

In addition, we also consider another luminosity distance indicator provided by GRBs, that can potentially be used to measure the luminosity distance out to higher redshift than SNIa. GRBs are not standard candles since their isotropic equivalent energetics and luminosities span 3–4 orders of magnitude. However, similar to SNIa it has been proposed to use correlations between various properties of the prompt emission and also of the afterglow emission to standardize GRB energetics (e.g. Ref. [25]). Recently, several empirical correlations between GRB observables were reported, and these findings have triggered intensive studies on the possibility of using GRBs as cosmological "standard" candles. However, due to the lack of low-redshift long GRB data to calibrate these relations, in a cosmology-independent way, the parameters of the reported correlations are given assuming an input cosmology and obviously depend on the same cosmological parameters that we would like to constrain. Thus, applying such relations to constrain cosmological parameters leads to biased results. In Ref. [26] this "circular problem" is naturally eliminated by marginalizing over the free parameters involved in the correlations; in addition, some results show that these correlations do not change significantly for a wide range of cosmological parameters [27,28]. Therefore, in this paper we use the 69 GRBs over a redshift range $z \in [0.17, 6.60]$ presented in Ref. [28], but we keep into account in our statistical analysis the issues related to the circular problem that are more extensively discussed in Ref. [26] and also the fact that all the correlations used to standardize GRBs have scatter and a poorly understood physics.

In the calculation of the likelihood from SNIa and GRBs, we have marginalized over the absolute magnitude M which is a nuisance parameter, as done in Refs. [29,30]:

$$\bar{\chi}^2 = A - \frac{B^2}{C} + \ln\left(\frac{C}{2\pi}\right), \tag{4}$$

where

$$A = \sum_i \frac{(\mu^{\rm data}-\mu^{\rm th})^2}{\sigma_i^2}, \qquad B = \sum_i \frac{\mu^{\rm data}-\mu^{\rm th}}{\sigma_i^2}, \qquad C = \sum_i \frac{1}{\sigma_i^2}. \tag{5}$$

2.2. Hubble measurements

The measurements of Hubble parameters can potentially to be a complementary probe in constraining cosmological parameters. The Hubble parameter characterizes the expansion rate of our universe at different redshifts, and depends on the differential age of the universe as a function of redshift:

$$H(z) = -\frac{1}{1+z}\frac{dz}{dt}. \tag{6}$$