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Deviation from the cosmological constant or systematic errors?

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ABSTRACT

In the work of Qi, Wang & Lu, gamma-ray bursts (GRBs) are used together with an earlier Type Ia supernova (SN Ia) data set to constrain the dark energy equation of state (EOS) in a nearly model-independent way. The improvements made by including GRBs show a slight shift of the dark energy EOS toward $w > -1$ at redshifts $z \gtrsim 0.5$. It is interesting that, when we have more SNe Ia, SNe Ia themselves also show the same trend. Motivated by the fact that both SNe Ia and GRBs seem to prefer a dark energy EOS greater than −1 at redshifts $z \gtrsim 0.5$, we perform a careful investigation of this situation, including more careful treatments of measurement errors of GRBs and cross-checking the results by using different ways of including GRBs. We find that the deviation of dark energy from the cosmological constant at redshifts $z \gtrsim 0.5$ is large enough that we should pay close attention to it with future observational data. Such a deviation may arise from some biasing systematic errors in the handling of SNe Ia and/or GRBs, or more interestingly from the nature of the dark energy itself.

Key words: supernovae: general – cosmological parameters – gamma-rays: bursts.

1 INTRODUCTION

It has been 10 years since the discovery of the cosmic acceleration (Riess et al. 1998; Perlmutter et al. 1999), which is attributed to a mysterious component – dark energy. In addition to the cosmological constant, a lot of dark energy models have been proposed to explain the cosmic acceleration (see e.g. Copeland, Sami & Tsujikawa 2006). Though the standard Λ cold dark matter (ΛCDM) model fits the observational data well, there are also a variety of other dark energy models that cannot be ruled out due to the precision of current data. It is therefore still a crucial issue whether the dark energy is simply the cosmological constant or not.

Among all kinds of observational sources, Type Ia supernovae (SNe Ia), which have been widely used as standard candles, are one of the most important classes of data that could impose significant constraints on the nature of dark energy. One of the important reasons for this is that SNe Ia provide data points along the redshifts and could therefore recover the nature of dark energy at different redshifts. However, due to the limitation of the redshifts of SNe Ia, it is difficult to study the nature of dark energy beyond a redshift of 1.7 with SNe Ia, while gamma-ray bursts (GRBs), as the most luminous astrophysical events observed today, extend the redshift to $z > 6$. After being calibrated, they could be used as complementary sources to SNe Ia at high redshifts in cosmology studies (see e.g. Schaefer 2007; Basilakos & Perivolaropoulos 2008), which has recently attracted much attention. At present, GRBs are still not as ideal standard candles as SNe Ia. The scatters of known luminosity relations of GRBs are still very large and they have a circularity problem due to the lack of low-redshift samples. In spite of this, works by many authors have put them forward in their cosmic applications. For example, recent advances include the introduction of new luminosity relations (Dainotti, Cardone & Capozziello 2008; Tsutsui et al. 2008) and the proposal of model-independent calibrations (Kodama et al. 2008; Li et al. 2008; Liang et al. 2008; Qi et al. 2008; Wang 2008). Among works using combined data of SNe Ia and GRBs, it is notable in Qi et al. (2008) that the improvements on the constraints made by including GRBs show that the dark energy equation of state (EOS) is slightly shifted towards $w > -1$ at redshifts $z \gtrsim 0.5$.[1] Since the results there are still totally consistent with the cosmological constant at 2σ confidence level and the inclusion of GRBs is very preliminary (only systematic errors of luminosity relations are included for simplicity), we cannot draw any concrete conclusion only from that. However, it is interesting that, when we have more

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[1] In the published version of Qi et al. (2008), there are typos in the luminosity relations, equations (16) and (17), and the typos are passed on to equation (21). However, the correct equations have been used in the calculations, so the results are unaffected. The typos have been corrected in third version on arXiv.

SN Ia samples, SNe Ia themselves also show the same trend, as was shown by fig. 17 in Kowalski et al. (2008). [To be fair, there are also other analyses with earlier SN Ia sets as well as with the Union set (Kowalski et al. 2008) that show signs of a possible increase in the dark energy EOS: see e.g. Alam et al. (2004), Alam, Sahni & Starobinsky (2007) and Sahni, Shafieloo & Starobinsky (2008). The advantages of the results in Qi et al. (2008) and fig. 17 in Kowalski et al. (2008) are that the redshift binned parametrization is used, which assumes less about the nature of the dark energy compared to simple parametrizations especially at high redshifts. For example, in Sullivan, Cooray & Holz (2007), where the redshift binned parametrization is adopted with earlier SN Ia sets, the constraints on the dark energy EOS at redshifts $z \gtrsim 0.5$ are still too weak. See also fig. 11 in Riess et al. (2007) for an illustration of priors imposed on the dark energy by a simple parametrization itself.] Because GRBs and SNe Ia are independent sources, the fact that they both seem to prefer a dark energy EOS greater than -1 at redshifts $z \gtrsim 0.5$ may be worth our increased attention. Motivated by this, we perform a careful investigation on this situation in this Letter.

2 METHODOLOGY

Standard candles impose constraints on cosmological parameters essentially through a comparison of the luminosity distance from observation with that from theoretical models. Observationally, data of the distance modulus are usually given instead in the literature, which is related to the luminosity distance by $\mu = 5\log d_L + 25$ with d_L in units of megaparsecs. Theoretically, the luminosity distance $d_L(z)$ depends on the geometry of the universe, i.e. the sign of Ω_k, and is given by

$$d_L(z) = (1+z)\frac{c}{H_0} \times \begin{cases} \frac{1}{\sqrt{|\Omega_k|}} \sinh\left[\sqrt{|\Omega_k|}\int_0^z \frac{\mathrm{d}\tilde{z}}{E(\tilde{z})}\right] & \text{if } \Omega_k > 0, \\ \int_0^z \frac{\mathrm{d}\tilde{z}}{E(\tilde{z})} & \text{if } \Omega_k = 0, \\ \frac{1}{\sqrt{|\Omega_k|}} \sin\left[\sqrt{|\Omega_k|}\int_0^z \frac{\mathrm{d}\tilde{z}}{E(\tilde{z})}\right] & \text{if } \Omega_k < 0, \end{cases} \quad (1)$$

where

$$E(z) = \left[\Omega_m(1+z)^3 + \Omega_x f(z) + \Omega_k(1+z)^2\right]^{1/2}, \quad \Omega_m + \Omega_x + \Omega_k = 1 \quad (2)$$

and

$$f(z) = \exp\left[3\int_0^z \frac{1+w(\tilde{z})}{1+\tilde{z}}\,\mathrm{d}\tilde{z}\right]. \quad (3)$$

Dark energy models enter through $f(z)$. In this Letter, we have adopted the redshift binned parametrization for the dark energy EOS, as proposed in Huterer & Cooray (2005), in which the redshifts are divided into several bins and the dark energy EOS is taken to be constant in each redshift bin but can vary from bin to bin. For this parametrization, $f(z)$ takes the form (Sullivan et al. 2007)

$$f(z_{n-1} < z \le z_n) = (1+z)^{3(1+w_n)} \prod_{i=0}^{n-1} (1+z_i)^{3(w_i - w_{i+1})}, \quad (4)$$

where w_i is the EOS parameter in the ith redshift bin defined by an upper boundary at z_i, and the zeroth bin is defined as $z_0 = 0$. Such a parametrization scheme assumes less about the nature of the dark energy, especially at high redshift, compared with other simple parametrizations, since independent parameters are introduced in every redshift range and it could, in principle, approach any functional form with the increase of the number of redshift bins (of course, we would need enough observational data to constrain all the parameters well). For a given set of observational data, the parameters w_i are usually correlated with each other, i.e. the covariance matrix

$$\mathbf{C} = \left\langle \boldsymbol{w}\boldsymbol{w}^{\mathrm{T}} \right\rangle - \langle \boldsymbol{w} \rangle \left\langle \boldsymbol{w}^{\mathrm{T}} \right\rangle \quad (5)$$

is not diagonal. A new set of dark energy EOS parameters $\widetilde{w}_i$ defined by

$$\widetilde{\boldsymbol{w}} = \mathbf{T}\boldsymbol{w} \quad (6)$$

is introduced to diagonalize the covariance matrix. The transformation of $\mathbf{T}$ advocated by Huterer & Cooray (2005) (see just below) has the advantage that the weights (rows of $\mathbf{T}$) are positive almost everywhere and localized in redshift fairly well, so the uncorrelated EOS parameters $\widetilde{w}_i$ are easy to interpret intuitively. The evolution of the dark energy with respect to the redshift could be estimated from these decorrelated EOS parameters. The transformation of $\mathbf{T}$ is determined as follows. First, we define the Fisher matrix

$$\mathbf{F} \equiv \mathbf{C}^{-1} = \mathbf{O}^{\mathrm{T}}\boldsymbol{\Lambda}\mathbf{O}, \quad (7)$$

and then the transformation matrix $\mathbf{T}$ is given by

$$\mathbf{T} = \mathbf{O}^{\mathrm{T}}\boldsymbol{\Lambda}^{1/2}\mathbf{O}, \quad (8)$$

except that the rows of the matrix $\mathbf{T}$ are normalized such that

$$\sum_j T_{ij} = 1. \quad (9)$$

In this Letter, we divided redshifts at points $z = 0.2, 0.5, 1$ and Markov chain Monte Carlo techniques are used with $\mathcal{O}(10^6)$ samples generated for each result. Since current observational data have only very weak constraints on the nature of dark energy at redshifts $z > 1$, we focus our analyses on the first three redshift bins.

For GRB data, we used the 69 GRBs compiled in Schaefer (2007) and the five luminosity relations mentioned there, i.e.

$$\log\frac{L}{1\,\mathrm{erg\,s^{-1}}} = a_1 + b_1 \log\left[\frac{\tau_{\mathrm{lag}}(1+z)^{-1}}{0.1\,\mathrm{s}}\right], \quad (10)$$

$$\log\frac{L}{1\,\mathrm{erg\,s^{-1}}} = a_2 + b_2 \log\left[\frac{V(1+z)}{0.02}\right], \quad (11)$$

$$\log\frac{L}{1\,\mathrm{erg\,s^{-1}}} = a_3 + b_3 \log\left[\frac{E_{\mathrm{peak}}(1+z)}{300\,\mathrm{keV}}\right], \quad (12)$$

$$\log\frac{E_\gamma}{1\,\mathrm{erg}} = a_4 + b_4 \log\left[\frac{E_{\mathrm{peak}}(1+z)}{300\,\mathrm{keV}}\right], \quad (13)$$

$$\log\frac{L}{1\,\mathrm{erg\,s^{-1}}} = a_5 + b_5 \log\left[\frac{\tau_{\mathrm{RT}}(1+z)^{-1}}{0.1\,\mathrm{s}}\right]. \quad (14)$$

For one of the luminosity relations above

$$y = a + bx, \quad (15)$$

where x and y denote the logarithm of the luminosity indicators and the logarithm of luminosity or energy of GRBs (see equations 10–14), the χ^2 is calculated by

$$\chi^2 = \sum_i \frac{(y_i - a - bx_i)^2}{\sigma^2_{\mathrm{tot},i}}, \quad (16)$$

where the summation runs over corresponding GRBs. Based on the discussion in Schaefer (2007), we safely ignore the correlations between different luminosity relations and simply add the χ^2 from the five luminosity relations. For the errors in the denominator of the right-hand side of equation (16), in Qi et al. (2008), only the systematic errors of the luminosity relations are taken into account for simplicity in the preliminary study of the evolution of the dark energy EOS including GRBs, i.e. it is set $\sigma^2_{\rm tot} = \sigma^2_{\rm sys}$. In this Letter, we include also the measurement errors of GRBs for a careful investigation, i.e. we set $\sigma^2_{\rm tot} = \sigma^2_{\rm mea} + \sigma^2_{\rm sys}$, where the systematic errors of the luminosity relations, $\sigma_{\rm sys}$, are derived by requiring the reduced χ^2 for corresponding luminosity relations equal to 1 and the measurement errors, $\sigma_{\rm mea}$, are given by $\sigma^2_{\rm mea} = \sigma^2_y + b^2\sigma^2_x$. For asymmetric measurement errors, the errors of the side near the line being fitted are used, as was done in Wang (2008). We fitted simultaneously the calibration parameters and cosmological parameters to avoid the circularity problem.

In addition to GRBs, we have used the Union compilation of SNe Ia from Kowalski et al. (2008), the baryon acoustic oscillations (BAO) measurement from Eisenstein et al. (2005) and $\Omega_m h = 0.213 \pm 0.023$ from Tegmark et al. (2004). We assumed the prior $\Omega_k = -0.014 \pm 0.017$ (Spergel et al. 2007) for the cosmic curvature.

3 RESULTS AND DISCUSSION

Fig. 1 shows the results derived from the combined data set mentioned above, including GRBs and SNe Ia. As stated earlier, calibration parameters of GRBs and cosmological parameters are fitted simultaneously, and measurement errors and systematic errors are both taken into account for GRBs. We can see that the deviation from the cosmological constant at redshifts $z \gtrsim 0.5$ turns out to be

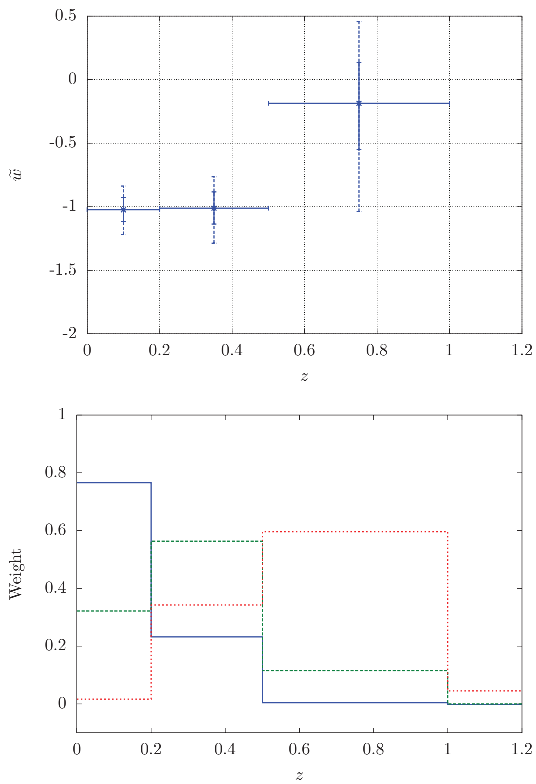

Figure 1. Estimates of the uncorrelated dark energy EOS parameters $\widetilde{w}_i$. Top: uncorrelated dark energy parameters versus redshift, in which the vertical error bars correspond to 1σ and 2σ confidence levels of $\widetilde{w}_i$ and the horizontal error bars span the corresponding redshift bins from which the contributions to $\widetilde{w}_i$ come most. Bottom: window functions for $\widetilde{w}_i$.

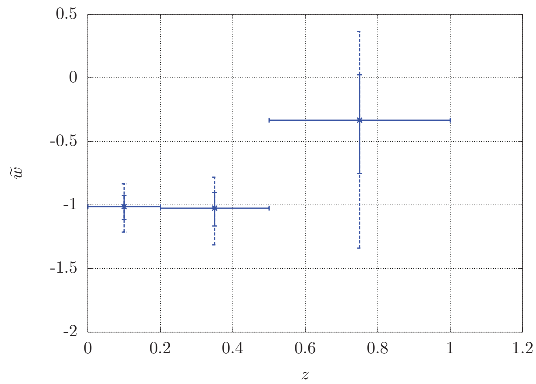

Figure 2. Estimates of the uncorrelated dark energy EOS parameters. Same as the top plot of Fig. 1 except that GRBs are not included in the constraint.

greater than the results in Qi et al. (2008), such that the EOS of -1 lies almost at the edge of the 2σ confidence interval. Though still consistent with the cosmological constant at 2σ confidence level, such a deviation should be large enough to attract our attention. Of course, if this deviation is just an illustration of statistical errors due to the limitation of current observational data, it would be meaningless and should disappear with the increase of the observational data. However, a comparison of the top plot of Fig. 1 with Fig. 2, for which GRBs are not included in the constraint, shows that SNe Ia alone shift the dark energy EOS at redshifts $z \gtrsim 0.5$ upwards from the cosmological constant and GRBs shift it a little more in the same direction. This means that both SNe Ia and GRBs prefer a dark energy EOS greater than -1 at redshifts $z \gtrsim 0.5$. One can argue that the independence of SNe Ia and GRBs reduces the possibility of the deviation arising from statistical errors. Such a deviation from the cosmological constant, if confirmed, may be caused by the nature of the dark energy itself or some biasing systematic errors in the observational data that should be excluded. For the latter, we would need to reconsider the process of calibrating SNe Ia and/or GRBs. It is notable that the recent CfA3 addition of SN Ia samples has brought SN Ia cosmology to the point where systematic uncertainties dominate (Hicken et al. 2009a,b). However, the former is more exciting for possibly ruling out the cosmological constant as the dark energy. Close attention should be paid to this deviation with future observational data.

To be more careful, we cross-checked our results by including GRBs in other different ways. For the results in Fig. 1, GRB data are not processed prior to being used to constrain the dark energy, i.e. the calibration of GRBs and constraining cosmological parameters are carried out simultaneously. In light of model-independent calibrations of GRBs in the literature (Kodama et al. 2008; Liang et al. 2008; Wang 2008), we performed the same analyses including instead the pre-processed GRB data from Wang (2008) and Cardone, Capozziello & Dainotti (2009). In Wang (2008), GRB data are summarized by a set of model-independent distance measurements. These distance measurements can be used directly to replace GRBs in constraining cosmological parameters. In Cardone et al. (2009), GRBs of redshift $z \leq 1.4$ are utilized to calibrate the luminosity relations based on a local regression estimate of distance moduli using the Union SN Ia sample (Kowalski et al. 2008), so the GRBs of redshifts $z > 1.4$, whose distance moduli are derived from the calibrated luminosity relations, can be used in the same way as SNe Ia. We present in Fig. 3 the results of including GRBs in the above two ways. The bottom plot of Fig. 3, for which the calibrated GRBs of redshifts $z > 1.4$ from Cardone et al. (2009) are used, is

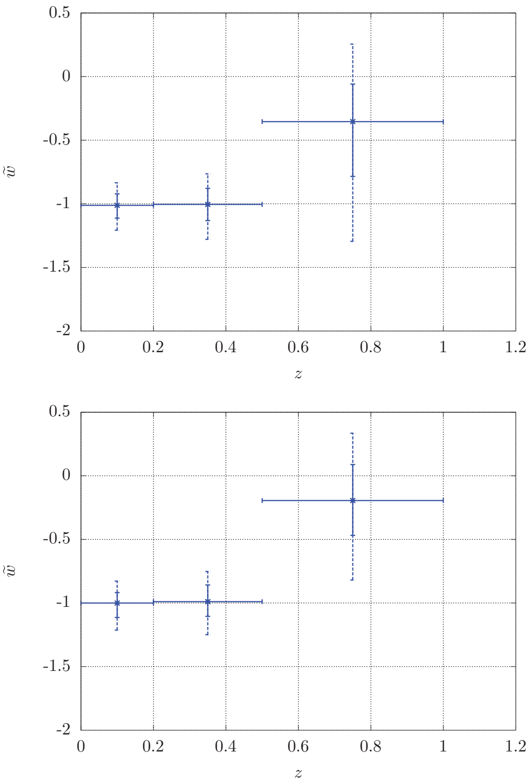

Figure 3. Estimates of the uncorrelated dark energy EOS parameters. Same as the top plot of Fig. 1 except that GRBs are included in model-independent ways. Top: GRBs are included by using the distance measurements from Wang (2008). Bottom: GRBs are included by using calibrated GRBs of redshifts $z > 1.4$ from Cardone et al. (2009).

consistent with the results in Fig. 1, except that the constraints are slightly tighter such that the cosmological constant has been ruled out at 2σ confidence level at redshifts $z \gtrsim 0.5$, which can be easily understood – some of the SNe Ia are used in both calibrating GRBs and constraining cosmological parameters. However, the top plot of Fig. 3, for which GRBs are included by using the distance measurements from Wang (2008), is somewhat different from the results in Fig. 1. Comparing with the results without including GRBs (see Fig. 2), we can see that including these distance measurements does not change the result much. In fact, it was shown in Wang (2008) that these distance measurements shift best-fitting parameter values towards the cosmological constant. Since the derivation of the distance measurements from GRBs involves quite a few intermediate steps and is carried out through the Markov chain Monte Carlo method, it is obscure what has caused the difference.

Finally, we would like to mention that in the above analyses we did not use the recent Constitution set of SNe Ia (Hicken et al. 2009b) and the BAO measurements presented in Percival et al. (2007). First, this is for the consistency of the data, because, in Cardone et al. (2009), GRBs are calibrated with the Union set of SNe Ia (Kowalski et al. 2008). Secondly, there seems to be some tension in these data sets. The results derived using them are quite different from the above. For the BAO measurements presented in Percival et al. (2007), see the argument in Kowalski et al. (2008). For SNe Ia, we noted that the Union set prefers a Hubble parameter around 70 km s^{-1} Mpc^{-1}, while the Constitution set are derived by adding CfA3 SNe Ia to the Union set using a Hubble parameter of 65 km s^{-1} Mpc^{-1}. We wonder whether this will cause any problems of consistency or not. Anyway, we present in Fig. 4 the results using

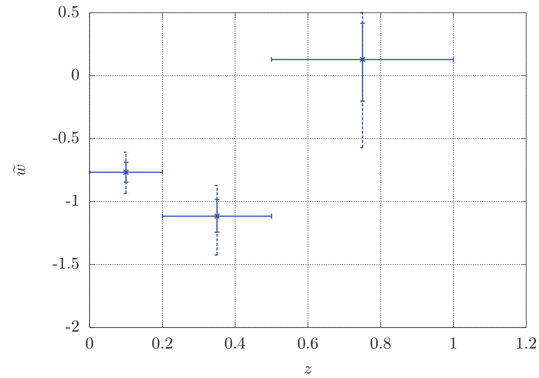

Figure 4. Estimates of the uncorrelated dark energy EOS parameters. Same as the top plot of Fig. 1 except that the Constitution set of SNe Ia from Hicken et al. (2009b) and the BAO measurements from Percival et al. (2007) are used instead.

the Constitution set of SNe Ia (Hicken et al. 2009b) and the BAO measurements from Percival et al. (2007), leaving the clarification of the differences between the data sets for the future. In spite of this, we can see from Fig. 4 that our conclusion on the dark energy EOS at redshifts $z \gtrsim 0.5$ is unaffected. See Shafieloo, Sahni & Starobinsky (2009) for a discussion on the behaviour of the dark energy at low redshifts derived from the Constitution set of SNe Ia (Hicken et al. 2009b) and the BAO measurements presented in Percival et al. (2007).

4 SUMMARY

In summary, motivated by the fact that both SNe Ia and GRBs seem to prefer a dark energy EOS greater than -1 at redshifts $z \gtrsim 0.5$, we perform a careful investigation of this situation, including more careful treatments of measurement errors of GRBs and cross-checking the results by using different ways of including GRBs. We find that the deviation of dark energy from the cosmological constant at redshifts $z \gtrsim 0.5$ is large enough that we should pay close attention to it with future observational data. Such a deviation may arise from some biasing systematic errors in the handling of SNe Ia and/or GRBs, or more interestingly from the nature of the dark energy itself.

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