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Observational constraints on the early dark energy model

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Abstract Dark energy can be studied by its influence on the expansion of the Universe. We investigate current constraints on early dark energy (EDE) achievable by the combined observational data from type Ia supernovae (557), baryon acoustic oscillations, the current cosmic microwave background and the observed Hubble parameter. We find that combining these data sets provides powerful constraints on early dark energy and the best fit values of the parameters in 68% and 95% confidence-level regions are: $\Omega_{\rm m0} = 0.2897^{+0.0149+0.0207}_{-0.0138-0.0194}$, $\Omega_{\rm e} = 0.0129^{+0.0272+0.0381}_{-0.0129-0.0129}$, $w_0 = -1.0415^{+0.0891+0.1182}_{-0.109-0.1604}$, and $h = 0.6988^{+0.0059+0.0083}_{-0.0058-0.0081}$.

Key words: cosmology — dark energy — cosmological parameters

1 INTRODUCTION

In modern cosmology, the unexpected discovery of the accelerating expansion of the universe was a very significant development. It was firstly discovered by observing type Ia supernovae (SNe Ia) (Riess et al. 1998; Perlmutter et al. 1999), which can be used as standard candles (Phillips 1993; Hamuy et al. 1995). The cosmic microwave background (CMB) measurements from the Wilkinson Microwave Anisotropy Probe (WMAP) (Spergel et al. 2003) and the large scale structure survey by the Sloan Digital Sky Survey (SDSS) (Tegmark et al. 2004a; Tegmark et al. 2004b) support the idea that we live in a universe which is accelerating its expansion. In order to explain this concept, there are two kinds of ideas, i.e. the existence of dark energy or modifications of the theory of gravity. The first scheme is the most commonly used one, but many other models have also been proposed, such as the Quintessence (Caldwell et al. 1998), Quintom (Feng et al. 2005), Holographic Dark Energy (Ke & Li 2005) and Chaplygin Gas models (Alcaniz et al. 2003). In addition, there are also many modified gravity models, such as the brane world (Deffayet et al. 2002) and $f(R)$ (Kerner 1982; Barrow & Ottewill 1983; Barrow & Cotsakis 1988; Li & Barrow 2007) and so on. Among them, the simplest model for the acceleration is the cosmological constant model.

With perfect observational data, one can compare the observational results with the theoretical predictions of different models using redshift-dependent quantities, such as SNe Ia (Phillips 1993), gamma-ray bursts (GRBs) (Dai et al. 2004; Ghirlanda et al. 2004) and X-ray gas mass fraction of galaxy clusters (Zhu et al. 2004). In addition, baryon acoustic oscillation (BAO) data from SDSS DR7 (Percival et al. 2010) and CMB observation (Komatsu et al. 2009) are also widely used to constrain various cosmological models.

In this work, we focus on the early dark energy model, in which a small fraction of dark energy is present in the early universe. The differences between early dark energy models and pure ΛCDM are particularly evident at high redshifts. This fraction of early dark energy is described by a new parameter $\Omega_{\rm e}$. Here we carry out the global fitting on the EDE model using the Markov Chain Monte Carlo (MCMC) method.

The paper is organized as follows: In Section 2, we briefly review the EDE model. In Section 3, we describe the current observational data we used. In Section 4, we perform the cosmic observation constraint and the results of the determination of the EDE parameters are presented. The last section is the conclusion.

2 REVIEW OF EARLY DARK ENERGY MODEL

Following the paper of Doran & Robbers (2006), we give a brief review of the general formula in the EDE model. In some dark energy models, the Hubble parameter is given by

$$\frac{H^2(a)}{H_0^2} = \frac{\Omega_{\rm m0}a^{-3}}{1-\Omega_{\rm X}(a)}, \tag{1}$$

where $\Omega_{\rm X}(a)$ is the evolution of the dark energy, a is the scale factor normalized to $a = 1$ today, and $\Omega_{\rm m0}$ is the matter (dark matter and baryonic) fractional energy density today. Here, we assumed a flat Universe. In the cosmological constant model, the fractional energy density evolves as

$$\Omega_\Lambda(a) = \frac{\Omega_\Lambda}{\Omega_\Lambda + \Omega_{\rm m0}a^{-3}}\,, \tag{2}$$

where Ω_Λ is dark energy today and we assume a flat universe, i.e. $\Omega_{\rm m0} + \Omega_\Lambda = 1$. The first generalization of this formula is to allow $w \neq -1$, which is achieved by Doran et al. (2001)

$$\Omega_{\rm X}(a) = \frac{1-\Omega_{\rm m0}}{1-\Omega_{\rm m0}+\Omega_{\rm m0}a^{3w_0}}. \tag{3}$$

Doran & Robbers (2006) added a term to include early dark energy. Its formula is as follows

$$\Omega_{\rm X}(a) = \frac{1-\Omega_{\rm m0}}{1-\Omega_{\rm m0}+\Omega_{\rm m0}a^{3w_0}} + \Omega_{\rm e}(1-a^\alpha). \tag{4}$$

where $\alpha > 0$. However, this form is not sufficient, because the evolution of $\Omega_{\rm X}(a)$ is connected to the equation of state w by the relation (Wetterich 2004)

$$\left(3w - \frac{a_{\rm eq}}{a+a_{\rm eq}}\right)\Omega_{\rm X}(1-\Omega_{\rm X}) = -{\rm d}\Omega_{\rm X}/{\rm d}\ln a, \tag{5}$$

where $a_{\rm eq}$ is the scale factor in matter-radiation equilibrium. Demanding that $w(a=1) = w_0$, which means that the parameter w_0 should indeed have its usual meaning, one is led to conclude that an additional term is needed in the numerator and that $\alpha = -3w_0$. This yields the final form of this parameterization, namely

$$\Omega_{\rm X}(a) = \frac{1-\Omega_{\rm m0}-\Omega_{\rm e}(1-a^{-3w_0})}{1-\Omega_{\rm m0}+\Omega_{\rm m0}a^{3w_0}} + \Omega_{\rm e}(1-a^{-3w_0}). \tag{6}$$

Many authors have worked extensively on this model, such as Linder & Robbers (2008).

3 CURRENT OBSERVATIONAL DATA

In order to test the EDE model, we have used the observational data currently available. In this section, we describe how we use these data.

3.1 Type Ia Supernovae Constraints

We use the 557 SNe Ia Union2 dataset (Amanullah et al. 2010). Following Garcia-Berro et al. (1999); Riazuelo & Uzan (2002); Acquaviva & Verde (2007) and Gannouji & Polarski (2008), one can obtain the corresponding constraints by fitting the distance modulus $\mu(z)$ as

$$\mu_{th}(z) = 5\log_{10}[D_L(z)] + \mu_0. \tag{7}$$

where $\mu_0 \equiv 42.38 - 5\log_{10} h$, and h is the Hubble constant H_0 in units of 100 km s^{-1} Mpc^{-1}. In a flat universe, the Hubble-free luminosity distance $D_L = H_0 d_L$ is

$$D_L(z) = (1+z)\int_0^z \frac{dz'}{E(z')}, \tag{8}$$

where $E(z) \equiv H(z)/H_0$.

For the SNe Ia dataset, the best fit values of the parameters can be determined by likelihood analysis, based on the calculation of

$$\chi^2_{\rm SN} = \sum_i^{557} \frac{[\mu_{\rm th}(z_i) - \mu_{\rm obs}(z_i)]^2}{\sigma^2(z_i)}. \tag{9}$$

3.2 Baryon Acoustic Oscillation Constraints

The BAO data come from SDSS DR7 (Percival et al. 2010). The data that we use are

$$\frac{r_{\rm s}(z_{\rm d})}{D_V(0.275)} = 0.1390 \pm 0.0037, \tag{10}$$

and

$$\frac{D_V(0.35)}{D_V(0.2)} = 1.736 \pm 0.065, \tag{11}$$

where the spherical average gives us the following effective distance measure (Eisenstein et al. 2005),

$$D_V(z) = \left[\left(\int_0^z \frac{dx}{H(x)}\right)^2 \frac{z}{H(z)}\right]^{1/3}, \tag{12}$$

and $r_{\rm s}(z_{\rm d})$ is the comoving sound horizon at the baryon drag epoch. Also, $z_{\rm d}$ can be obtained by using a fitting formula (Eisenstein & Hu 1998)

$$z_{\rm d} = \frac{1291(\Omega_{\rm m}h^2)^{0.251}}{1+0.659(\Omega_{\rm m}h^2)^{0.828}}[1 + b_1(\Omega_{\rm b}h^2)^{b_2}], \tag{13}$$

with

$$b_1 = 0.313(\Omega_{\rm m}h^2)^{-0.419}[1 + 0.607(\Omega_{\rm m}h^2)^{0.674}], \tag{14}$$
$$b_2 = 0.238(\Omega_{\rm m}h^2)^{0.223}. \tag{15}$$

The function $r_{\rm s}(z)$ is the comoving sound horizon size

$$r_{\rm s}(z) = \frac{c}{\sqrt{3}}\int_0^{1/(1+z)} \frac{da}{a^2 H(a)\sqrt{1 + (3\Omega_{\rm b}/(4\Omega_\gamma)a)}}, \tag{16}$$

where Ω_γ is the fractional energy density of relativistic neutrinos and photons today. Here $\Omega_\gamma = 2.469 \times 10^{-5}h^{-2}$ for $T_{\rm CMB} = 2.725\,$K, so the χ^2 for the BAO data is given by

$$\chi^2_{\rm BAO} = \left(\frac{r_{\rm s}(z_{\rm d})/D_V(z=0.275) - 0.1390}{0.0037}\right)^2 + \left(\frac{D_V(z=0.35)/D_V(z=0.2) - 1.736}{0.065}\right)^2. \tag{17}$$

3.3 Cosmic Microwave Background Constraints

The CMB shift parameter R is provided by (Bond et al. 1997)

$$R(z_*) = \frac{\sqrt{\Omega_\mathrm{m} H_0^2}}{\sqrt{|\Omega_k|}} \mathrm{sinn}\Big[\sqrt{|\Omega_k|}\int_0^{z_*}\frac{dz'}{H(z')}\Big]. \tag{18}$$

where $\mathrm{sinn}(x)$ is $\sinh(x)$ for $\Omega_k > 0$, x for $\Omega_k = 0$, and $\sin(x)$ for $\Omega_k < 0$, respectively. Here the redshift z_* (the decoupling epoch of photons) is obtained by using the fitting function (Hu & Sugiyama 1996)

$$z_* = 1048\left[1 + 0.00124(\Omega_\mathrm{b}h^2)^{-0.738}\right]\left[1 + g_1(\Omega_\mathrm{m}h^2)^{g_2}\right],$$

where

$$\begin{aligned} g_1 &= 0.0783(\Omega_\mathrm{b}h^2)^{-0.238}\left[1 + 39.5(\Omega_\mathrm{b}h^2)^{0.763}\right]^{-1}, \\ g_2 &= 0.560\left[1 + 21.1(\Omega_\mathrm{b}h^2)^{1.81}\right]^{-1}. \end{aligned}$$

In addition, the acoustic scale is related to the distance ratio and is expressed as

$$l_A = \frac{\pi}{r_\mathrm{s}(z_*)}\frac{c}{\sqrt{|\Omega_k|}}\mathrm{sinn}[\sqrt{|\Omega_k|}\int_0^{z_*}\frac{dz'}{H(z')}]. \tag{19}$$

Following Komatsu et al. (2011), the χ^2 for the CMB data is

$$\chi^2_\mathrm{CMB} = (x_i^\mathrm{th} - x_i^\mathrm{obs})(C^{-1})_{ij}(x_j^\mathrm{th} - x_j^\mathrm{obs}), \tag{20}$$

where $x_i = (l_A, R, z_*)$ is a vector and $(C^{-1})_{ij}$ is the inverse covariance matrix. The seven-year WMAP observations (Komatsu et al. 2011) give the maximum likelihood values: $l_A(z_*) = 302.09$, $R(z_*) = 1.725$ and $z_* = 1091.3$. In Komatsu et al. (2011), the inverse covariance matrix is also given as follows

$$(C^{-1}) = \begin{pmatrix} 2.305 & 29.698 & -1.333 \\ 29.698 & 6825.270 & -113.180 \\ -1.333 & -113.180 & 3.414 \end{pmatrix}. \tag{21}$$

3.4 Observational Hubble Data (OHD)

The Hubble parameter can be written in the following form

$$H(z) = -\frac{1}{1+z}\frac{dz}{dt}. \tag{22}$$

So, through measuring dt/dz, we can obtain $H(z)$. In Jimenez & Loeb (2002), Jimenez et al. (2003) and Simon et al. (2005), the authors indicated that it is possible to use absolute ages of passively evolving galaxies to compute values of dt/dz. The galaxy spectral data used by Simon et al. (2005) come from the Gemini Deep Deep Survey (Abraham et al. 2004) and archival data (Dunlop et al. 1996; Dunlop et al. 1996; Spinrad et al. 1997; Treu et al. 1999; Treu et al. 2001; Treu et al. 2002; Nolan et al. 2003). Detailed calculations of dt/dz can be found in Simon et al. (2005), so we do not discuss them here. Currently, we have a set of 12 values of the Hubble parameter versus redshift in total (see table 2 of Stern et al. 2010). A particularly attractive feature of this test is that differential ages are less sensitive to systematic errors than absolute ages (Jimenez et al. 2004).

We can use these data to constrain different kinds of dark energy models and modified gravity models by minimizing the quantity

$$\chi^2_{\rm OHD} = \sum_{j=1}^{9} \frac{[H(z_j) - H_{\rm obs}(z_j)]^2}{\sigma^2_{{\rm H},j}}. \quad (23)$$

This test has already been used to constrain several cosmological models (Yi & Zhang 2007; Lin et al. 2009; Samushia & Ratra 2006; Wei & Zhang 2007b; Zhang et al. 2007; Wei & Zhang 2007a; Zhang & Wu 2007; Dantas et al. 2007; Zhang & Zhu 2008; Wu & Yu 2007; Wei & Zhang 2007b; Lu et al. 2009; Xu & Lu 2010).

4 METHOD AND RESULTS

In our analysis, we perform a global fitting to determine the cosmological parameters using the MCMC method. The MCMC method is based on the publicly available **CosmoMC** package (Lewis & Bridle 2002) and the **modified CosmoMC** package (Rapetti et al. 2005; Allen et al. 2008). For our models, we have modified these packages to add the new EDE parameter. We use a top-hat prior for the cosmic age, i.e., $10\,{\rm Gyr} < t_0 < 20\,{\rm Gyr}$.

In our calculations, we have taken the total likelihood function $L \propto {\rm e}^{-\chi^2/2}$ to be the products of the separate likelihoods of SN, BAO, CMB and OHD. Then we get χ^2 as

$$\chi^2 = \chi^2_{\rm SN} + \chi^2_{\rm BAO} + \chi^2_{\rm CMB} + \chi^2_{\rm OHD}. \quad (24)$$

The results of the best values of the cosmological parameters with 68% and 95% confidence-level errors in the EDE model are as follows: $\Omega_{\rm m0} = 0.2897^{+0.0149+0.0207}_{-0.0138-0.0194}$, $\Omega_{\rm e} = 0.0129^{+0.0272+0.0381}_{-0.0129-0.0129}$, $w_0 = -1.0415^{+0.0891+0.1182}_{-0.109-0.1604}$, and $h = 0.6988^{+0.0059+0.0083}_{-0.0058-0.0081}$.

In Figure 1, we show the one dimensional probability distribution for each parameter and two dimensional plots for joint parameter distributions in the EDE model. The following is some discussion of these findings:

(1) We use the current dataset to fit the EDE model and our result is more tight when compared with the result in papers by Doran & Robbers (2006) and Basilakos (2010).
(2) The best fit value of $\Omega_{\rm e}$ is 0.0129. It is small but not negligible in the early universe. However, we can also see that $\Omega_{\rm e} = 0$ is not excluded from the 68% confidence level.
(3) The best fit value of $\Omega_{\rm m}$ is 0.2897. This value is larger than the value in the cosmological constant model. The reason is that the early dark energy contributes to the expansion of the universe, and the cosmological constant is accordingly small.
(4) The best fit value of w_0 is -1.0415. It is approximately equal to -1. These results indicated that the current observations tend to make the EDE model reduce to the flat cosmological constant model.
(5) In our work, h is consistent with the updated observation (Spergel et al. 2007).

5 CONCLUSIONS AND DISCUSSION

In this paper, we make a thorough investigation of the EDE model with a completely consistent analysis of the combined observations. We use more complete combinations of the observational datasets from the 557 SN Ia (Amanullah et al. 2010) data, the BAO measurement for the values of $[r_{\rm s}(z_{\rm d})/D_V(0.2), D_V(0.35)/D_V(0.2)]$ (Percival et al. 2010), the OHD at twelve different redshifts and the CMB observation (Komatsu et al. 2009) for the maximum likelihood values of $[l_A(z_*), R(z_*), z_*]$ and their inverse covariance matrix. We carry out global fitting of

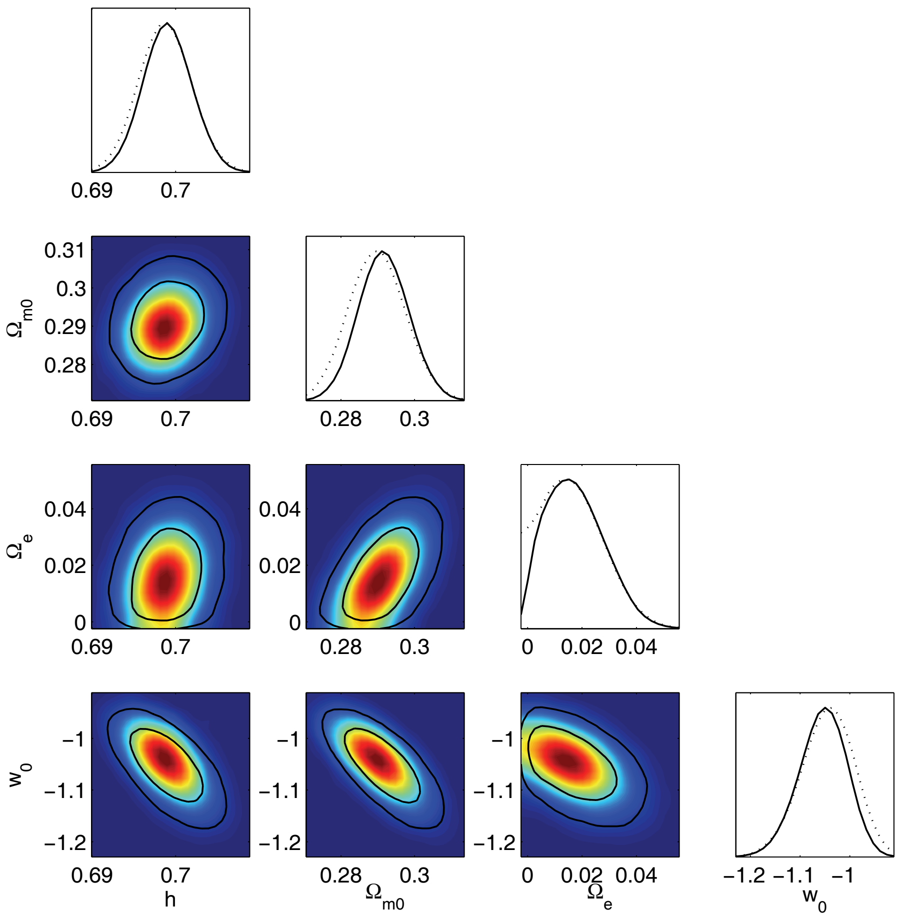

Fig. 1 1-D constraints on individual parameters $(h, \Omega_{\rm m0}, \Omega_{\rm e}, w_0)$ and 2-D contours on these parameters with 68% and 95% joint confidence-level errors using a combination of the observational data from SN, BAO, CMB and OHD in the EDE model. Dotted lines in the 1-D plots show the mean likelihood of the samples and the solid lines are marginalized probabilities for the parameters in the EDE model (Lewis & Bridle 2002).

the EDE model using the MCMC method. The constraint results are shown as follows. For the EDE model, the best fit values of the parameters in 68% and 95% confidence-level regions are: $\Omega_{\rm m0} = 0.2897^{+0.0149+0.0207}_{-0.0138-0.0194}$, $\Omega_{\rm e} = 0.0129^{+0.0272+0.0381}_{-0.0129-0.0129}$, $w_0 = -1.0415^{+0.0891+0.1182}_{-0.109-0.1604}$, and $h = 0.6988^{+0.0059+0.0083}_{-0.0058-0.0081}$. The result indicates that there may be a small fraction of dark energy in the early stages of our universe. Much more work should be done in this subject.

Acknowledgements The data fitting is based on the publicly available **CosmoMC** package, a Markov Chain Monte Carlo (MCMC) code.

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