Constraints on dynamical dark energy: an update

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Abstract. By combining data from cosmic microwave background experiments (most notably from the latest WMAP 3 years’ results) with large scale structure data, luminosity measurements of type Ia supernovae and Lyman-α observations, we place new constraints on the dark energy equation of state parameter $w_X$ and its evolution. Using the dark energy parameterization introduced by Hannestad and Mortsell (2004 J. Cosmol. Astropart. Phys. JCAP09(2004)001), we constrain the equation of state parameters to $-1.23 < w_0 < -0.88$ and $-1.29 < w_1 < -0.78$ at 95% C.L. Although our limits on $w_0$ and $w_1$ are improved with respect to previous analyses, cosmological data do not strongly rule out the possibility of a varying-with-redshift equation of state.

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1. Introduction

Recent combined analysis of cosmic microwave background (CMB) anisotropies and complementary cosmological data from large scale clustering have provided an excellent confirmation of the standard model of structure formation (see e.g. [1]–[3]).

The price-tag of this success story is a very puzzling consequence: the evolution of the universe is dominated by a mysterious form of energy, $X$, termed dark energy, (an unclustered negative pressure component of the mass–energy density), with a present-day energy density fraction $\Omega_X \simeq 2/3$ and equation of state $w_X \sim -1$ (see e.g. [2, 4]). This discovery may turn out to be one of the most important contributions to physics in our generation. Hence it is especially important to consider all possible schemes for dark energy.

A true cosmological constant $\Lambda$ may be at work here, but it has a difficult theoretical interpretation. However, it is entirely possible that a dynamical mechanism is giving rise to the observed acceleration of the present Universe. Some of the popular proposed candidates to explain the observations are a slowly rolling scalar field, ‘quintessence’ [5, 6], or a ‘k-essence’ scalar field with non canonical kinetic terms in the Lagrangian [7]–[11], and string-inspired models such as the contribution of nonlinear short distance physics to vacuum energy [8], and modified Friedman equations at late time [9] or large distances [10].

Given the lack of a well-established physical model for the dark energy component, most of the recent analyses have compared observations with purely phenomenological models with the main goal of ruling out a cosmological constant. The main predictions of the cosmological constant are essentially an unclustered, homogeneous, component with constant energy density and equation of state $w_X = -1$. Any possible hint from the data for $w_X \neq -1$, redshift dependence or dark energy clustering will therefore suggest a different physics from $\Lambda$.

Recent combined analyses of CMB, galaxy clustering and Supernovae Type Ia (SN-Ia) luminosity distance data, have constrained a constant-with-redshift equation of state to be $w_X = -0.926^{+0.051}_{-0.075}$ at 68% C.L. [2] and therefore are compatible with a cosmological constant, ruling out several alternative models. More recently, new and powerful constraints coming from Lyman-$\alpha$ observations of large scale clustering have further improved the constraint to $w_X = -1.04^{+0.065}_{-0.066}$ at 95% C.L. [3]. Similar conclusions, with larger error bars but in an independent way, have been obtained by the recent detection of integrated Sachs–Wolfe effect by cross correlating Wilkinson Microwave Anisotropy Probe (WMAP) with large scale galaxy surveys (see e.g. [12] and references therein). Moreover, the detection of baryonic acoustic oscillation in the SDSS red luminous galaxies correlation function [13] opens a new area of investigation.

Other analyses have recently constrained dynamical dark energy models, focusing on the possibility of detecting a variation with redshift of $w_X$. While analyses of the so-called gold SN-Ia dataset by Riess et al [14] were suggesting a possible redshift dependence of the equation of state, the more recent observations from the SuperNovae Legacy Survey (SNLS [15]) are in full agreement with a constant-with-redshift equation of state. Combined analyses of CMB, SN-Ia and large scale structure are also compatible with the simple assumption of a cosmological constant [16].

In this study, we make use of the most recent datasets, including Lyman-$\alpha$, in order to put the best possible constraints on the equation of state $w_X$ parameterizing it with a phenomenological function and therefore allowing the possibility of having a dynamical $w_X$. In the next section, we describe our analysis method. In section 3, we present our results and finally, in the last section we derive our conclusions.
2. Analysis

The analysis method adopted is based on a modified version of the publicly available Markov Chain Monte Carlo package \texttt{cosmomc} \cite{17}. We sample the following ten-dimensional (10D) set of cosmological parameters, adopting flat priors on them: the physical baryon and CDM densities, $\omega_b = \Omega_b h^2$ and $\omega_c = \Omega_c h^2$, the ratio of the sound horizon to the angular diameter distance at decoupling, $\theta_s$, the scalar spectral index and the overall normalization of the spectrum, $n$ and $A$ at $k = 0.002 \text{ Mpc}^{-1}$, and, finally, the optical depth to re-ionization, $\tau$. Furthermore, we consider purely adiabatic initial conditions and we impose flatness.

We model the dark energy component as a fluid of equation of state $P_X = w_X \rho_X$ where $w_X$ is evolving with the scale factor $a$ following:

$$w_X(a) = w_0 w_1 \frac{a^q + a_s^q}{a^q w_1 + a_s^q w_0},$$

where $a = (1 + z)^{-1}$ is indeed the scale factor normalized to the value of one today. $w_0$ and $w_1$ are constants and describe the asymptotic behaviour of $w$:

$$w_X(z) \rightarrow \begin{cases} w_0 & \text{for } 1 + z \rightarrow 0 \\ w_1 & \text{for } 1 + z \rightarrow \infty. \end{cases}$$

The two additional parameters $a_s$ and $q$ describe the scale factor at transition and its gradient. This parameterization, introduced by \cite{18}, has the advantage of being simple and practical. This is just one of the possible phenomenological models proposed in the literature \cite{18}--\cite{27} but, given the current status of observations, we argue that for a preliminary investigation for a varying with redshift $w_X$ all the models should provide equivalent results. Moreover, since current data are not yet able to strongly constrain the nature of perturbations in the dark energy component (see \cite{28} and, more recently, \cite{29} for a discussion about anisotropic stresses), we model perturbations as fluctuations in a fluid with sound speed $c_s^2 = 1$ and no anisotropic stresses.

We include the three-year data \cite{2} (temperature and polarization) with the routine for computing the likelihood supplied by the WMAP team and available at the \texttt{LAMBDA} web site. We also include the CBI \cite{30}, VSA \cite{31}, ACBAR \cite{32} and BOOMERANG-2k2 \cite{1} measurements of the CMB. In addition to the CMB data, we also consider the constraints on the real-space power spectrum of galaxies from the SLOAN galaxy redshift survey (SDSS) \cite{33} and 2dF \cite{34} and Lyman-alpha forest clouds \cite{35, 36} from the SDSS, the gold sample of the recent supernova type Ia data \cite{14} and latest SNLS supernovae data\cite{15}. The details of the analysis are the same as those in \cite{3}.

The MCMC convergence diagnostics is done on eight chains though the Gelman and Rubin ‘variance of chain mean’/‘mean of chain variances’ $R$ statistic for each parameter. Our 1 -- $D$ and 2 -- $D$ constraints are obtained after marginalization over the remaining ‘nuisance’ parameters, again using the programs included in the \texttt{cosmomc} package. We consider large scale structure data restricting the analysis to a range of scales over which the fluctuations are assumed to be in the linear regime ($k < 0.2 \text{ h}^{-1} \text{ Mpc}$) and we marginalize over a bias $b$ considered as an additional nuisance parameter. Furthermore, we make use of the HST measurement of the Hubble parameter $H_0 = 100 \text{ h} \text{ km s}^{-1} \text{ Mpc}^{-1}$ \cite{37} by multiplying the likelihood by a Gaussian likelihood function centred around $h = 0.72$ and with a standard deviation $\sigma = 0.08$. Finally, we include a top-hat prior on the age of the universe: $10 < t_0 < 20 \text{ Gyrs}$.

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Figure 1. Likelihood contours in the $w_0 - w_1$ plane from our analysis in the case of $w_X \geq -1$. The contours correspond to the 68 and 95% confidence levels respectively. The top panel shows results from the analysis without Lyman-$\alpha$ data, while the bottom panel includes it.

3. Results

The main results of our analysis are plotted in figures 1 and 2, where we plot the $2 - D$ likelihood contours on the $w_0$ vs $w_1$ plane for different combinations of priors and datasets, obtained after marginalizing over all remaining nuisance parameters. In figure 1, we plot likelihood contours in the $(w_0, w_1)$ plane for the joint analyses of CMB + SN-Ia + HST + LSS data (top panel) and including Lyman-$\alpha$ data but restricting the analysis to values of $w_X \geq -1$.

As we can see from the bottom panel of figure 1, considering all the mentioned dataset with the exception of Ly-$\alpha$ forest and including a prior $w_X > -1$ one obtains the constraint $w_0 < -0.81$ and $w_1 < -0.52$ at 95% C.L. Including the Lyman-$\alpha$ data increases the constraints to $w_0 < -0.90$ and $w_1 < -0.63$ at 95% C.L. We found that the other parameters, choosed in the range $0 < a_s < 1$, $0 < q < 10$ are poorly constrained even when Lyman-$\alpha$ are included.

In figure 2, we plot likelihood contours in the $(w_0, w_1)$ plane for the joint analyses of CMB + SN-Ia + HST + LSS + Ly-$\alpha$ but now allowing the analysis to values of $w_X \leq -1$. In this case, the parameter constraints are $-1.23 < w_0 < -0.88$ and $-1.29 < w_1 < -0.78$. As we can see, there is a large parameter space of models compatible with $w_x < -1$ that seems also slightly preferred from the data.
Figure 2. Likelihood contours in the $w_0 - w_1$ plane from our analysis including also the possibility of $w_X \leq -1$. The contours correspond to the 68 and 95% confidence levels respectively.

Models with $w_X < -1$ break the weak energy conservation condition and are often considered as unstable and unrealistic. There are however physical models that can satisfy such conditions. For example, interacting dark energy models (see e.g. [38] and [39]) are stable and may provide an effective equation of state $w_X < -1$ without violating the weak energy condition. Also in tachyon models, which are based on string theory models, the instabilities which are a feature of phantom models do not exist (see e.g. [40]). Finally, models with a Gauss–Bonnet term (which are physically well motivated from quantum corrections) are not unstable and also present an effective equation of state $w_X < -1$ (see e.g. [29]).

4. Conclusions

In this short paper, we use the most recent data from cosmic microwave background anisotropies and polarization, galaxy clustering, Lyman-α and supernovae type Ia observations to place new constraints on the dark energy equation of state parameter $w_X$. We found that current data provide new and stronger constraints. In particular, considering the previous analysis of Hannestad and Mortsell [18], we are now able to fully constrain at 95% C.L. the parameters $w_0$ and $w_1$, while only lower limits were previously obtained. Our results are in agreement with a cosmological constant even if models with a varying-with-redshift equation of state are still not completely ruled out. Let us note, however, that a possible problem with parameterizations which try to describe dynamical dark energy models (specifically scalar field models), is the fact that they do not provide a complete description of the dependence of both the equation of state and perturbations on the scalar field initial conditions (see e.g. [41]). Due to that, phenomenological parameterizations may have a limited power to unveil the real nature of dark energy.

References

[1] MacTavish C J et al 2005 Preprint astro-ph/0507503
[2] Spergel D N et al 2006 Preprint astro-ph/0603449

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[3] Seljak U, Slosar A and McDonald P 2006 Preprint astro-ph/0604335

[4] Melchiorri A, Mersini L, Odman C J and Trodden M 2002 Phys. Rev. D 68 043509 (Preprint astro-ph/0211522)

[5] Wetterich C 1988 Nucl. Phys. B 302 668

[6] Caldwell R R, Dave R and Steinhardt P J 1997 Phys. Rev. Lett. 80 1582 (Preprint astro-ph/9708069)

[7] Armendiariz-Picon C, Damour T and Mukhanov V 1999 Phys. Lett. B 458 209 (Preprint hep-th/9904075)

[8] Mersini L, Bastero-Gil M and Kanti P 2001 Phys. Rev. D 64 043508 (Preprint hep-ph/0101210, hep-ph/0106134)

Bastero-Gil M, Frampton P and Mersini L 2002 Phys. Rev. D 65 106002 (Preprint hep-th/0110167)

Bastero-Gil M and Mersini L 2003 Phys. Rev. D 67 103519 (Preprint hep-th/0205271)

[9] Freese K and Lewis M 2002 Phys. Lett. B 540 1–8 (Preprint astro-ph/0201229)

[10] Dvali G, Gabadadze G and Porrati M 2000 Phys. Lett. B 485 (Preprint hep-th/0005016)

Dvali G and Gabadadze G 2001 Phys. Rev. D 64 043508 (Preprint hep-th/0005016)

Dvali G and Turner M 2003 Preprint astro-ph/0301510

[11] Chiba T, Okabe T and Yamaguchi M 2000 Phys. Rev. D 62 023511 (Preprint astro-ph/9912463)

[12] Corasaniti P S, Giannantonio T and Melchiorri A 2005 Phys. Rev. D 71 123521 (Preprint astro-ph/0504115)

[13] Eisenstein D J et al 2005 Astrophys. J. 633 560 (Preprint astro-ph/0501171)

[14] Riess A G et al (Supernova Search Team Collaboration) 2004 Astrophys. J. 607 665 (Preprint astro-ph/0402512)

[15] Astier P et al 2005 Astron. Astrophys. 447 31 (Preprint astro-ph/0501210)

[16] Zhao G B, Xia J Q, Feng B and Zhang X 2006 Preprint astro-ph/0603621

[17] Lewis A and Bridle S 2002 Phys. Rev. D 66 103511 (Available from http://cosmologist.info)

[18] Hannestad S and Mortsell E 2004 J. Cosmol. Astropart. Phys. JCAP09(2004)001 (Preprint astro-ph/0407259)

[19] Corasaniti P S et al 2004 Preprint astro-ph/0406608

[20] Gong Y 2004 Preprint astro-ph/0405446

[21] Gong Y 2004 Preprint astro-ph/0401207

[22] Hessels D and Perivolaropoulos L 2004 Preprint astro-ph/0401556

[23] Feng B, Wang X L and Zhang X M 2004 Preprint astro-ph/0404224

[24] Alam U, Sahni V and Starobinsky A A 2004 Preprint astro-ph/0406672

[25] Alam U, Sahni V and Starobinsky A A 2004 J. Cosmol. Astropart. Phys. JCAP06(2004)08

[26] Corasaniti P S and Copeland E-J 2002 Preprint astro-ph/0205544

[27] Jassal H K, Bagla J S and Padmanabhan T 2004 Preprint astro-ph/0404378

[28] Bean R and Dore O 2004 Phys. Rev. D 69 083503

Caldwell R R, Dave R and Steinhardt P J 1998 Phys. Rev. Lett. 80 1582–5

[29] Koivisto T and Mota D F 2006 Preprint astro-ph/0606078

[30] Readhead A C S et al 2004 Astrophys. J. 609 498

[31] Dickinson C et al 2004 Mon. Not. R. Astron. Soc. 353 732

[32] Kuo C L et al 2002 Am. Astron. Soc. Meeting 201

[33] Tegmark M et al (SDSS Collaboration) 2003 Preprint astro-ph/0310725

[34] Cole S et al 2005 Mon. Not. R. Astron. Soc. 362 505

[35] McDonald P et al 2006 Astrophys. J. Suppl. 163 80 (Preprint astro-ph/0405013)

[36] McDonald P et al 2005 Astrophys. J. 635 761 (Preprint astro-ph/0407377)

[37] Freedman W L et al 2001 Astrophys. J. 553 47 (Preprint astro-ph/0012376)

[38] Das S, Corasaniti P S and Khoury J 2006 Phys. Rev. D 73 083509

[39] Brookfield A W et al 2006 Phys. Rev. Lett. 96 061301

[40] Bagla N, Jassal H and Padmanabhan T 2003 Phys. Rev. D 67 063504

[41] Abram L and Finelli F 2001 Phys. Rev. D 64 083513

Mota D F and van de Bruck C 2004 Astron. Astrophys. 421 71–81

Bartolo N, Corasaniti P S, Liddle A R and Malquarti M 2004 Phys. Rev. D 70 043532

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