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Exploring hints for dark energy density evolution in light of recent data

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ABSTRACT

Considering a quadratic parameterization of the dark energy density, we explore signatures of evolution using data from gas mass fraction in clusters, type Ia supernova, BAO and CMB. We find – excluding CMB data – a preference for an evolution of $\rho_{de}(z)$ towards smaller values as the redshift increases, a result consistent with a recent study using the BAO DR11 data by Delubac et al. (2015).

1. Introduction

The ΛCDM model is the simplest cosmological model that fits a varied set of observational data: type Ia supernova (SNIa), baryon acoustic oscillations (BAO), Cosmic microwave background radiation (CMBR), growth of structure, etc. [1]. In this setup, the cosmological constant Λ drives the current accelerated expansion of the universe, detected for the first time using type Ia supernovae [2,3]. Although successful in fitting the data, the model is awkward in many ways; for example, we do not know the mechanism to produce such a constant in the first place. We also do not expect to live in a special epoch where the contribution of this constant is of the same order of magnitude as the non-relativistic matter contribution. This problem in particular is known as the "cosmic" coincidence problem.

From a theoretical point of view, it is most natural to think that this contribution comes from an evolving source (with epoch), whose connection with the universe expansion is under study. Dark energy (DE) is the name of this mysterious source [4].

Different DE models have been proposed to provide the mechanism that explains the observational data. There are models where a new field component is assumed to fill the universe, known as quintessence [5–10], and models where the mechanism is triggered by using a modified gravity theory [11–13].

In the absence of consensus regarding a theoretical description for cosmic acceleration, theorists have proposed using the equation of state (EoS) parameter $w(a) = p/\rho$, where a is the scale factor, as a useful phenomenological description [4].

In this context in [14], using the Constitution data set for SNIa [15], and the Chevalier–Polarski–Linder (CPL) parameterization for $w(a)$ [16,17],

$$w(a) = w_0 + (1-a)w_1, \tag{1}$$

with w_0 and w_1 being the free parameters to be fixed by observations, the authors found a reconstructed deceleration parameter that apparently shows a rapid variation at small redshift, around $z \simeq 0.2$. However, once the BAO and CMB data are added into the analysis, the best fit result changes completely, showing no sign of variation at the small redshift in agreement with what is expected in the ΛCDM model. In [18] similar results were found, under the assumption of a flat universe using the Union 2 data set [19]. In [20] we revisit this problem using the Union 2 data set, extending the analysis to allow for curved spacetime.

In [21], using data from gas mass fraction in galaxy clusters f_{gas}, we encountered the same apparent behavior found previously using SNIa [14,18,20].

SNIa are standardizable candles from which we measure the luminosity distance. In the case of the gas mass fraction, we measure the X-ray emission, which enables us to estimate the baryonic (mostly gas) and total mass, assuming the intracluster gas is in hydrostatic equilibrium, from which we measure the angular diameter distance to the cluster [22]. Because the f_{gas} data span a

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similar redshift range as the SNIa, but depend on a completely different physics, this finding is certainly intriguing.

Although the statistical significance of this effect is small, the consistency between the results using SNIa and f_{gas} moves us to deepen the study of this effect at low redshift.

We also studied the possible dependence of this result – a low redshift transition of the deceleration parameter – with different parameterizations. In [23] we used five different types of parameterizations and the result was always consistent with that found using CPL. However, the analysis based on using $w(z)$ increases the errors in the parameters we want to constrain. The problem with using $w(z)$ as the focus of study was demonstrated in [24] (see also [25]). The essential problem is the observational quantity, as the luminosity distance or the angular diameter distance depends on $w(z)$ through a double integral, smearing out the information about $w(z)$ itself and its time variation.

As the ΛCDM model is by definition a model with a constant DE density, in this work we focus on signals of a possible departure from this trend. In this context, as was explained in the previous paragraph, it is not efficient to use $w(z)$ or a particular parameterization of it; instead, we work directly with the dark energy density, whatever that may be. This strategy was started in [26], and [27], where the authors demonstrated the advantage of using the energy density instead of the EoS parameter as the main probe to constraint.

In this paper we investigate possible hints of evolution of the dark energy density in light of recent data. We use gas mass fraction in clusters [22] – 42 measurements of f_{gas} in clusters extracted from [28] – and also in type Ia supernovae (SNIa) from the Lick Observatory Supernova Search (LOSS) compilation sample [29]. We also consider the constraints obtained from baryon acoustic oscillations (BAO) and cosmic microwave background radiation (CMB). The BAO measurements considered in our analysis are obtained from the WiggleZ experiment [39], the SDSS DR7 BAO distance measurements [40], and 6dFGS BAO data [41]. We also include background CMB information by using the Planck data [30] to probe the expansion history up to the last scattering surface. We have also performed the analysis using the WMAP 9-yr covariance matrix from [42], with no significant changes.

The paper is organized as follows. In the next section we describe what we have learned from the $w(z)$ parameterization. Then, we describe how to implement the interpolation method to constrain the DE density model using the observational data available. After that, we present the results of our study, first using SNIa and f_{gas} data and then within a joint analysis. We end with a discussion of the results.

2. Insights from the reconstructed deceleration parameter

Observational cosmology is essentially based on quantities derived from the Hubble function. For example, using both type Ia supernova or galaxy cluster data, the key functions are written in terms of the comoving distance from the observer to the redshift z given by

$$r(z) = \frac{c}{H_0}\frac{1}{\sqrt{-\Omega_k}}\sin\sqrt{-\Omega_k}\int_0^z \frac{dz'}{E(z')}, \tag{2}$$

where $E(z) = H(z)/H_0$ contains the cosmology. For example, for the case of the ΛCDM model, the function is

$$E^2(z) = \Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_k(1+z)^2 + \Omega_\Lambda. \tag{3}$$

Here Ω_m comprise both the baryonic and non-baryonic DM. We know the radiation component is negligible at low redshift; in fact, we know $h^2\Omega_r = 2.47\times 10^{-5}$ from [30]. However, if we want to constrain our model using data from BAO and CMB, we have to use it, because these probes refer to both the last scattering redshift and the drag epoch.

In practice, by using the CPL parameterization (1) for the DE component, and after testing it against the observational data, we get the best fit values of the parameters, which give us the best Hubble function $E(z) \equiv H(z)/H_0$ that agrees with the data. From it, following previous works [14,18,20], we reconstruct the deceleration parameter function

$$q(z) = (1+z)\frac{1}{E(z)}\frac{dE(z)}{dz} - 1. \tag{4}$$

In order to motivate the next section, we will repeat the calculation with recent data. We use gas mass fraction in clusters extracted from [28], and also type Ia supernovae (SNIa) from the LOSS compilation sample [29]. From now on we assume a spatially flat universe ($\Omega_k = 0$).

The SNIa data give the luminosity distance $d_L(z) = (1+z)r(z)$. We fit the SNIa with the cosmological model by minimizing the χ^2 value defined by

$$\chi^2_{SNIa} = \sum_{i=1}^{586}\frac{[\mu(z_i) - \mu_{obs}(z_i)]^2}{\sigma^2_{\mu i}}, \tag{5}$$

where $\mu(z) \equiv 5\log_{10}[d_L(z)/\mathtt{Mpc}] + 25$ is the theoretical value of the distance modulus, μ_{obs} is the corresponding observed one, and $\sigma_{\mu i}$ is the error associated with it. As explained in [29], the error comprises three components: the uncertainty from light-curve fits, a component due to the peculiar velocity of each SNIa, and an intrinsic scatter term which depends on the sample (see Table 1 in [29]).

The gas mass fraction data we use span a redshift range $0.05 < z < 1.1$. The f_{gas} data are quoted for a flat ΛCDM reference cosmology with $h = H_0/100\ \mathrm{km\,s^{-1}\,Mpc^{-1}} = 0.7$ and $\Omega_M = 0.3$. To obtain the restrictions we use the model function from [31]:

$$f_{gas}^{\Lambda CDM}(z) = \frac{b\Omega_b}{(1+0.19\sqrt{h})\Omega_M}\left[\frac{d_A^{\Lambda CDM}(z)}{d_A(z)}\right]^{3/2}, \tag{6}$$

where b is a bias factor motivated by gas-dynamical simulations which suggest the baryon fraction in clusters is slightly lower than for the universe as a whole. From [32] $b = 0.824 \pm 0.0033$ is obtained. Following [31] we adopt a Gaussian prior on b, taking into account systematic uncertainties, so we use $b = 0.824 \pm 0.089$. In the analysis we also use standard Gaussian priors on $\Omega_b h^2 = 0.02205 \pm 0.00028$ and $h = 0.72 \pm 0.08$ from Planck and WMAP polarization [30].

The use of SNIa and f_{gas} data separately, as demonstrated in [21], generates a behavior that is consistent between them. For that reason, in what follows we show first the result considering both probes together. Given the two data sets are consistent each other, we use the standard χ^2 analysis.

In the analysis (see the details in Appendix A) we consider h, Ω_m, w_0, w_1, Ω_b and b as free parameters. As we mentioned, we have added Gaussian priors for h, Ω_b and b. After the analysis the best fit values are those shown in Table 1.

Using the best fit values for the CPL parameters (w_0, w_1), the deceleration parameter (4), with error propagation, is shown in Fig. 1. From Fig. 1, we notice that the combined action of SNIa and f_{gas} data suggest a universe in transit, from a decelerated expansion regime to an accelerated one, with the transition redshift $z \simeq 0.8$, in agreement with ΛCDM, and also a slowing down of the acceleration at recent times, a result that seems to be supported at a 2σ level.