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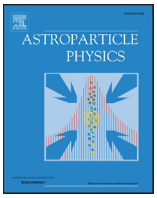

Observational constraints to a unified cosmological model

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ABSTRACT

We propose a phenomenological unified model (UM) for dark matter and dark energy based on an equation of state parameter w that scales with the arctan of the redshift. The free parameters of the model are three constants: Ω_{b0}, α and β. Parameter α dictates the transition rate between the matter dominated era and the accelerated expansion period. The ratio β/α gives the redshift of the equivalence between both regimes. Cosmological parameters are fixed by observational data from primordial nucleosynthesis (PN), supernovae of the type Ia (SNIa), gamma-ray bursts (GRBs) and baryon acoustic oscillations (BAOs). The calibration of the 138 GRB events is performed using the 580 SNIa of the Union2.1 data set and a new set of 79 high-redshift GRB is obtained. The various sets of data are used in different combinations to constraint the parameters through statistical analysis. The UM is compared to the ΛCDM model and their differences are emphasized.

1. Introduction

The recent technological improvement in the space observations deeply altered cosmology. In the end of the 1990s, the measurement of the luminosity distance of type Ia supernovae (SNIa) unveiled an accelerating cosmic expansion at recent times [1,2]. This result was later confirmed by other works using different sets of data [3] such as the cosmic microwave background radiation (CMB) [4], baryon acoustic oscillations (BAOs) [5,6] and even the relatively recent gamma-ray burst (GRB) data [7–9]. As long as one assumes a homogeneous and isotropic cosmological background, the cosmic acceleration at low redshifts seems an indisputable observational truth.[1]

The simplest theoretical way of describing cosmic acceleration is through the cosmological constant Λ, a negative energy density uniformly distributed throughout the cosmos. The resulting ΛCDM cosmological model [17] is robust when confronted to observational data, although it is not a comfortable solution mainly due to the lack of a clear interpretation of the physical meaning of Λ in terms of the known fundamental interactions. This very fact relegates Λ to the mysterious "dark sector" of the universe. It is completed by the gravitationally bound cold dark matter (CDM), whose nature is also unknown.

In face of these two unexplained components, one is tempted to unify them in a single dark fluid. This unified model (UM) would have to be capable of accelerating the universe at recent times and also provide a dust dominated epoch toward the past in order to accommodate structure formation. This is our motivation to introduce the UM described in Section 2.1. There is a plethora of cosmological models based on the same idea [18]; they are build either based on theoretical motivations [19–29] or on phenomenological ones [30–38]. Our model is built on phenomenological grounds.

The UM is a dynamical model developed from a specific functional form chosen for the parameter w of the equation of state $p = w\rho$, where p is the pressure related to the cosmic component of density ρ: w is given in terms of the arctan function. This way, the universe filled with the unified fluid passes smoothly from a matter-like behavior ($w \simeq 0$) to a dark-energy-like dynamics ($w \simeq -1$). This property is justified theoretically once the history of the universe demands a matter-dominated era with decelerated expansion ($2 \lesssim z \lesssim 10,000$) followed by an accelerated period dominated by dark energy ($z \lesssim 2$) [10]. Our goal is to treat dark matter and dark energy on the same footing.

The unified scenario for the dark components is meaningful only if one can constraint the free parameters of the UM by using a large number of observational data. For this end, we will use the already mentioned SNIa, BAO and GRB data plus information on the baryon density parameter Ω_{b0} coming from primordial nucleosynthesis (PN) data.[2]

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[1] Inhomogeneous cosmological model, such as those in Refs. [10–16], present alternative explanation to the apparent present-day cosmic acceleration.

[2] More on Ω_{b0} and PN bellow (Section 3.1).

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We used Union2.1 compilation [39] for obtaining the distance modulus μ of the supernovae as a function of their redshift z. For the GRB, we employed data in Ref. [40], which include 29 GRB in addition to the set of 109 GRB of Ref. [41]. Also, we payed special attention to the construction of the calibration curve of the GRB. The procedure involved an interpolation to the points in the plot of μ as function of z. We noticed that the common interpolation methods, such as linear and cubic interpolation techniques, are not the best-quality ones. In fact, Akima's method [42] is the one which provides a curve that naturally connects the observational points without bumps or discontinuities. We devoted special care to the GRB data as they rise as new good candidates for standard candles at very high redshifts, with great potential of revealing additional cosmological information.

The paper is organized as follows. Section 2 presents our UM for the dark sector of the universe; in addition, the basic equation of the ΛCDM model are reviewed. This prepares the ground for data fitting aiming to constraint the free parameters of both UM and ΛCDM. The statistical treatment is performed in Section 3 after the cosmological data sets used in our analysis have been discussed. The physical consequences of the data fit for the various combinations of data (PN, SNIa, GRB and BAO) are also addressed in Section 3 and further discussed in Section 4, where we also point out our final comments.

2. Cosmological set up

This section presents the two cosmological models that are constrained by observational data in this paper. The first one is a phenomenological model that we call UM. The second one is the fiducial ΛCDM model, considered here for the sake of comparison.

2.1. Unified model

Our framework will be a flat universe filled with baryonic matter and a unified component of dark matter and dark energy. The Hubble function for this model is

$$H = H_0\sqrt{\Omega_U(z,\alpha,\beta) + \Omega_{b0}(1+z)^3}, \tag{1}$$

where $\Omega_U(z,\alpha,\beta)$ is the density parameter of the unified fluid,

$$\Omega_U(z) = \Omega_{U0}\exp\left\{\int_0^z 3\frac{\left[1+w_U(z')\right]}{1+z'}dz'\right\},$$

which is subjected to the constraint

$$\Omega_{U0} + \Omega_{b0} = 1 \tag{2}$$

and depends on the redshift z and three free parameter Ω_{b0}, α and β to be determined from adjustment to the available observational data.

The parameter w_U of the equation of state is a function of z and describes the transition from the matter dominated dynamics to the acceleration domination epoch. It is convenient to define [43]

$$w_U = \frac{1}{\pi}\arctan(\alpha z - \beta) - \frac{1}{2}. \tag{3}$$

The idea to propose a phenomenological parameterization which unifies the dark components is not new. For instance, in the works [35,36] the authors use an expression exhibiting plots resembling those built with Eq. (3); however, there is an important conceptual difference between their reasoning and ours. Whereas in this paper we adopt a dynamical approach, the authors of [35,36] use a kinematic one. The advantage of a kinematic model in which one chooses to parameterize the deceleration parameter q in terms of the redshift z—as that of Ref. [36]—is that very few assumptions on the nature of the dark components are taken *a priori*. On the other hand, dynamical models parameterizing $w(z)$ are more physical in the sense that they enable a meaningful perturbation theory (once they presuppose Einstein's equation of gravity and standard cosmological assumptions).

Parameter α gives the transition rate between the decelerated expansion and the recent accelerated phase of the universe's evolution. Parameter β provides the value for w_U today (null redshift). Moreover,

$$z_{eq} = \frac{\beta}{\alpha} \tag{4}$$

is the redshift corresponding to the equivalence between the dark energy and the dark matter energy densities. This expression is obtained by taking $w_U = -1/2$, the average of the values $w = 0$ and $w = -1$.

Fig. 1 (a) shows that the larger is α the greater is the transition rate (if β is kept constant). Fig. 1(b) illustrates the fact that the value of the redshift of equivalence grows with β (for a given α).

2.2. ΛCDM

We shall fit the concordance ΛCDM model to the observations using the same data sets and techniques applied to our UM for comparison.

The ΛCDM Hubble function for the flat universe is:

$$H(z) = H_0\sqrt{(\Omega_{b0} + \Omega_{d0})(1+z)^3 + (1 - \Omega_{b0} - \Omega_{d0})}, \tag{5}$$

where Ω_{b0} is the density parameter for the baryonic matter and Ω_{d0} is the density parameter for the dark matter component. In the ΛCDM cosmology, the constant $\Omega_\Lambda = (1 - \Omega_{b0} - \Omega_{d0})$ is the density parameter of the dark energy, interpreted as a cosmological constant. We define the effective equation of state parameter w_{dark} for

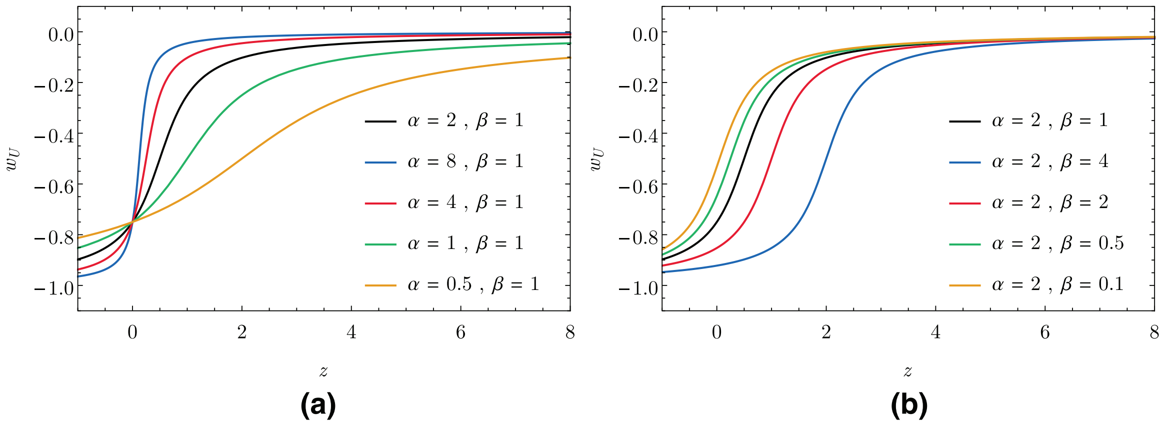

Fig. 1. Curves of w_U as a function of z for different values of parameters α and β—see Eq. (3).