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Constraints on modified Chaplygin gas from recent observations and a comparison of its status with other models

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Abstract

In this Letter, a modified Chaplygin gas (MCG) model of unifying dark energy and dark matter with the exotic equation of state $p_{\mathrm{MCG}} = B\rho_{\mathrm{MCG}} - \frac{A}{\rho^{\alpha}_{\mathrm{MCG}}}$ is constrained from recently observed data: the 182 Gold SNe Ia, the 3-year WMAP and the SDSS baryon acoustic peak. It is shown that the best fit value of the three parameters (B, B_s, α) in MCG model are $(-0.085, 0.822, 1.724)$. Furthermore, we find the best fit $w(z)$ crosses -1 in the past and the present best fit value $w(0) = -1.114 < -1$, and the 1σ confidence level of $w(0)$ is $-0.946 \leqslant w(0) \leqslant -1.282$. Finally, we find that the MCG model has the smallest χ^2_{min} value in all eight given models. According to the Akaike Information Criterion (AIC) of model selection, we conclude that recent observational data support the MCG model as well as other popular models.

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Keywords: Modified Chaplygin gas (MCG); Dark energy; Akaike Information Criterion (AIC)

1. Introduction

The type Ia supernova (SNe Ia) explorations [1], the cosmic microwave background (CMB) results from WMAP [2] observations, and surveys of galaxies [3] all suggest that the universe is speeding up rather than slowing down. The accelerated expansion of the present universe is usually attributed to the fact that dark energy is an exotic component with negative pressure. Many kinds of dark energy models have already been constructed such as ΛCDM [4], quintessence [5], phantom [6], generalized Chaplygin gas (GCG) [7], quintom [8], holographic dark energy [9], and so forth.

On the other hand, to remove the dependence of special properties of extra energy components, a parameterized equation of state (EOS) is assumed for dark energy. This is also commonly called the model-independent method. The parameterized EOS of dark energy which is popularly used in parameter best fit estimations, describes the possible evolution of dark energy. For example, $w = w_0 = \mathrm{const}$ [10], $w(z) = w_0 + w_1 z$ [11], $w(z) = w_0 + \frac{w_1 z}{1+z}$ [12], $w(z) = w_0 + \frac{w_1 z}{(1+z)^2}$ [13], $w(z) = \frac{1+z}{3}\frac{A_1+2A_2(1+z)}{X} - 1$ (here $X \equiv A_1(1+z) + A_2(1+z)^2 + (1 - \Omega_{0m} - A_1 - A_2)$) [14]. The parameters w_0, w_1, or A_1, A_2 are obtained by the best fit estimations from cosmic observational datasets.

It is well known that the GCG model has been widely used to interpret the accelerating universe. In the GCG approach, dark energy and dark matter can be unified by using an exotic equation of state. Also, a modified Chaplygin gas (MCG) as a extension of the generalized Chaplygin gas model has already been applied to describe the current accelerating expansion of the universe [15–18]. The constraint on parameter B in MCG model, i.e., the added parameter relative to GCG model, is discussed briefly by using the location of the peak of the CMB radiation spectrum in Ref. [19]. In this Letter, we study the constraints on the best fit parameters (B, B_s, α) and EOS in the MCG model from recently observed data: the latest observations of the 182 Gold type Ia Supernovae (SNe) [20], the 3-year WMAP CMB shift parameter [21] and the baryon acoustic oscillation (BAO) peak from Sloan Digi-

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tal Sky Surver (SDSS) [22]. The result of this study indicates that the best fit value of parameters (B, B_s, α) in MCG model are $(-0.085, 0.822, 1.724)$. Furthermore, we find the best fit $w(z)$ crosses -1 in the past and the present best fit value $w(0) = -1.114 < -1$, and the 1σ confidence level of $w(0)$ is $-0.946 \leqslant w(0) \leqslant -1.282$. At last, because the emphasis of the ongoing and forthcoming research is shifting from estimating specific parameters of the cosmological model to model selection [23], it is interesting to estimate which model for an accelerating universe is distinguish by statistical analysis of observational datasets out of a large number of cosmological models. Therefore, by applying the recent observational data to the Akaike Information Criterion (AIC) of model selection, we compare the MCG model with other seven general cosmological models to see which model is better. It is found that the MCG model has almost the same support from the data as other popular models. In the Letter, we perform an estimation of model parameters using a standard minimization procedure based on the maximum likelihood method.

The Letter is organized as follows. In Section 2, the MCG model is introduced briefly. In Section 3, the best fit value of parameters (B, B_s, α) in the MCG model are given from the recent observations of SNe Ia, CMB and BAO, and we present the evolution of the best fit of $w(z)$ with 1σ confidence level with respect to redshift z. The preferred cosmological model is discussed in Section 4 according to the AIC. Section 5 is the conclusion.

2. Modified Chaplygin gas model

For the modified Chaplygin gas model, the energy density ρ and pressure p are related by the equation of state [15]

$$p_{\mathrm{MCG}} = B\rho_{\mathrm{MCG}} - \frac{A}{\rho_{\mathrm{MCG}}^{\alpha}}, \tag{1}$$

where A, B, and α are parameters in the model.

Considering the FRW cosmology, by using the energy conservation equation: $d(\rho a^3) = -p\,d(a^3)$, the energy density of MCG can be derived as [18]

$$\rho_{\mathrm{MCG}} = \rho_{0\mathrm{MCG}}\big[B_s + (1 - B_s)(1+z)^{3(1+B)(1+\alpha)}\big]^{\frac{1}{1+\alpha}}, \tag{2}$$

for $A \neq -1$, where a is the scale factor, $B_s = \frac{A}{(1+B)\rho_0^{1+\alpha}}$. In order to unify dark matter and dark energy for the MCG model, the MCG fluid is decomposed into two components: the dark energy component and the dark matter component, i.e., $\rho_{\mathrm{MCG}} = \rho_{\mathrm{de}} + \rho_{\mathrm{dm}}$, $p_{\mathrm{MCG}} = p_{\mathrm{de}}$. Then according to the relation between the density of dark matter and redshift:

$$\rho_{\mathrm{dm}} = \rho_{0\mathrm{dm}}(1+z)^3, \tag{3}$$

the energy density of the dark energy in the MCG model can be given by

$$\begin{aligned}\rho_{\mathrm{de}} &= \rho_{\mathrm{MCG}} - \rho_{\mathrm{dm}} \\ &= \rho_{0\mathrm{MCG}}\big[B_s + (1 - B_s)(1+z)^{3(1+B)(1+\alpha)}\big]^{\frac{1}{1+\alpha}} \\ &\quad - \rho_{0\mathrm{dm}}(1+z)^3.\end{aligned} \tag{4}$$

Next, we assume the universe is filled with two components, one is the MCG component, and the other is baryon matter component, i.e., $\rho_t = \rho_{\mathrm{MCG}} + \rho_b$. The equation of state of dark energy can be derived as [18]

$$\begin{aligned}w_{\mathrm{de}} &= (1 - \Omega_{0b})\big[B_s + (1 - B_s)(1+z)^{3(1+B)(1+\alpha)}\big]^{-\frac{\alpha}{1+\alpha}} \\ &\quad \times \big[-B_s + B(1 - B_s)(1+z)^{3(1+B)(1+\alpha)}\big] \\ &\quad \times \big((1 - \Omega_{0b})\big[B_s + (1 - B_s)(1+z)^{3(1+B)(1+\alpha)}\big]^{\frac{1}{1+\alpha}} \\ &\quad - \Omega_{0\mathrm{dm}}(1+z)^3\big)^{-1},\end{aligned} \tag{5}$$

where $\Omega_{0\mathrm{dm}}$ and Ω_{0b} are present values of the dimensionless dark matter density and baryon matter component.

Furthermore, in a flat universe, making use of the Friedmann equation, the Hubble parameter H can be written as

$$H^2 = \frac{8\pi G\rho_t}{3} = H_0^2 E^2, \tag{6}$$

where $E^2 = (1 - \Omega_{0b})[B_s + (1 - B_s)(1+z)^{3(1+B)(1+\alpha)}]^{\frac{1}{1+\alpha}} + \Omega_{0b}(1+z)^3$. H_0 denotes the present value of the Hubble parameter. When $B = 0$, Eq. (6) is reduced to the GCG scenario.

In the following section, on the basis of Eq. (6), we will apply the recently observed data to find the best fit parameters $(\Omega_{0b}, B, B_s, \alpha)$ in MCG model. For simplicity, we will displace parameters $(\Omega_{0b}, B, B_s, \alpha)$ with θ in the following section.

3. The best fit parameters from present cosmological observations

Since type Ia Supernovae behave as Excellent Standard Candles, they can be used to directly measure the expansion rate of the universe up to high redshifts ($z \geqslant 1$) for comparison with the present rate. Therefore, they provide direct information on the universe's acceleration and constrain the dark energy model. Theoretical dark energy model parameters are determined by minimizing the quantity

$$\chi^2_{\mathrm{SNe}}(H_0, \theta) = \sum_{i=1}^{N} \frac{(\mu_{\mathrm{obs}}(z_i) - \mu_{\mathrm{th}}(z_i))^2}{\sigma^2_{\mathrm{obs};i}}, \tag{7}$$

where $N = 182$ for the Gold SNe Ia data [20], $\sigma^2_{\mathrm{obs};i}$ are errors due to flux uncertainties, intrinsic dispersion of SNe Ia absolute magnitude and peculiar velocity dispersion respectively. The theoretical distance modulus μ_{th} is defined as

$$\begin{aligned}\mu_{\mathrm{th}}(z_i) &\equiv m_{\mathrm{th}}(z_i) - M \\ &= 5\log_{10}\big(D_L(z)\big) + 5\log_{10}\left(\frac{H_0^{-1}}{\mathrm{Mpc}}\right) + 25,\end{aligned} \tag{8}$$

where

$$D_L(z) = H_0 d_L(z) = (1+z)\int_0^z \frac{H_0\,dz'}{H(z'; H_0, \theta)}, \tag{9}$$

μ_{obs} is given by supernovae dataset, and d_L is the luminosity distance.

The structure of the anisotropies of the cosmic microwave background radiation depends on two eras in cosmology, i.e.,