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Cosmological constraints on ghost dark energy in the Brans–Dicke theory by using MCMC approach

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ABSTRACT

By using a Markov Chain Monte Carlo simulation, we investigate cosmological constraints on the ghost dark energy (GDE) model in the framework of the Brans–Dicke (BD) theory. A combination of the latest observational data of the cosmic microwave background radiation data from seven-year WMAP, the baryon acoustic oscillation data form the SDSS, the supernovae type Ia data from the Union2 and the X-ray gas mass fraction data from the Chandra X-ray observations of the largest relaxed galaxy clusters are used to perform constraints on GDE in the BD cosmology. In this paper, we consider both flat and non-flat universes together with interaction between dark matter and dark energy. The main cosmological parameters are obtained as: $\Omega_b h^2 = 0.0223^{+0.0016}_{-0.0013}$, $\Omega_c h^2 = 0.1149^{+0.0088}_{-0.0104}$ and $\Omega_k = 0.0005^{+0.0025}_{-0.0073}$. In addition, the Brans–Dicke parameter ω is estimated as $1/\omega \simeq 0.002$.

1. Introduction

Accelerating expansion of the Universe [1,2] can be explained either by a missing energy component usually called "dark energy" (DE) with an exotic equation of state, or by modifying the underlying theory of gravity on large scales. The famous examples of the former approach include scalar field models of DE such as quintessence [3,4], K-essence [5,6], tachyon [7,8], phantom [9–11], ghost condensate [12,13], quintom [14–16], holographic DE [17], agegraphic DE [18,19] and so forth. For a comprehensive review on DE models, see [20,21]. The latter approach for explanation of the acceleration expansion is based on the modification of the underlying theory of gravity on large scales such as $f(R)$ gravity [22] and braneworld scenarios [23–26].

Among various models of DE, the so called ghost dark energy (GDE) has attracted a lot of interest in recent years. The origin of DE in this model comes from Veneziano ghosts in QCD theory [27–30]. Indeed, the contribution of the ghosts field to the vacuum energy in curved space or time-dependent background can be regarded as a possible candidate for DE [31,32]. The magnitude of this vacuum energy is of order $\Lambda^3_{\mathrm{QCD}} H$, where H is the Hubble parameter and Λ_{QCD} is the QCD mass scale. With $\Lambda_{\mathrm{QCD}} \sim 100$ MeV and $H \sim 10^{-33}$ eV, $\Lambda^3_{\mathrm{QCD}} H$ gives the right order of magnitude $\sim(3 \times 10^{-3}\ \mathrm{eV})^4$ for the observed dark energy density [31]. The advantages of GDE model compared to other DE models is that it is totally embedded in standard model and general relativity, therefore one needs not to introduce any new parameter, new degree of freedom or to modify gravity. The dynamical behavior of GDE model in flat universe have been studied [33]. The study was also generalized to the universe with spacial curvature [34]. The instability of the GDE model against perturbations was studied in [35]. In [36,37] the correspondence between GDE and scalar field models of DE was established. In the presence of bulk viscosity and varying gravitational constant, the GDE model was investigated in [38]. Other features of the GDE model have been investigated in Refs. [39–43]. The cosmological constraints on this model have been considered by some authors [33,43,44].

Recently, scalar tensor theories have been reconsidered extensively. One important example of the scalar tensor theories is the BD theory of gravity which was introduced by Brans and Dicke in 1961 to incorporate Mach's principle in Einstein's theory of gravity [45]. This theory also passes the observational tests in the solar system domain [46]. In addition, BD theory can be tested by the cosmological observations such as the cosmic microwave background (CMB) and large scale structure (LSS) [47–51]. Since the GDE model has a dynamic behavior, it is more reasonable to consider this model in a dynamical framework such as BD theory.

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It was shown that some features of GDE in BD cosmology differ from Einstein's gravity [52]. For example, while the original DE is instable in all range of the parameter spaces in standard cosmology [35], it leads to a stable phase in BD theory [53]. In the framework of BD cosmology, the ghost model of DE has been studied [52]. It is also of great interest to see whether the GDE model in the framework of the BD theory is compatible with observational data or not.

In this paper, cosmological constraints on GDE in the BD theory (GDEBD) [52] theory is performed by using the Marko Chain Monte Carlo (MCMC) simulation. The used observational datasets are as follows: cosmic microwave background radiation (CMB) from WMAP7 [54], 557 Union2 dataset of type Ia supernova [55], baryon acoustic oscillation (BAO) from SDSS DR7 [56], and the cluster X-ray gas mass fraction from the Chandra X-ray observations [57]. To put the constraints, the modified CosmoMC [58] code is used.

The organization of this paper is as follows. In Section 2, we review the formalism of the GDE in the framework of Brans–Dicke cosmology. In Section 3 the methods which are used in this paper to analyze the data are introduced. Section 4 contains the results of the MCMC simulation and we conclude our paper in Section 5.

2. Interacting ghost dark energy in the Brans–Dicke theory in a non-flat universe

Let us first review the formalism of the interacting GDE in the framework of BD theory in a non-flat universe [52]. The action of the BD theory in the canonical form may be written [59]

$$S=\int d^4x\sqrt{g}\left(-\frac{1}{8\omega}\phi^2R+\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi+L_M\right), \tag{1}$$

where R is the Ricci scalar and ϕ is the BD scalar field. Varying the action with respect to the metric $g_{\mu\nu}$ and the BD scalar field ϕ, yields

$$\phi G_{\mu\nu}=-8\pi T^M_{\mu\nu}-\frac{\omega}{\phi}\left(\phi_{,\mu}\phi_{,\nu}-\frac{1}{2}g_{\mu\nu}\phi_{,\lambda}\phi^{,\lambda}\right) -\phi_{;\mu;\nu}+g_{\mu\nu}\Box\phi, \tag{2}$$

$$\Box\phi=\frac{8\pi}{2\omega+3}T^{M\lambda}_{\lambda}, \tag{3}$$

where $T^M_{\mu\nu}$ stands for the energy-momentum tensor of the matter fields. The line element of the Friedmann–Robertson–Walker (FRW) universe is

$$ds^2=dt^2-a^2(t)\left(\frac{dr^2}{1-kr^2}+r^2d\Omega^2\right), \tag{4}$$

where $a(t)$ is the scale factor, and k is the curvature parameter with $k=-1,0,1$ corresponding to open, flat, and closed universes, respectively. Nowadays, there are some evidences in favor of closed universe with a small positive curvature ($\Omega_k\simeq 0.01$) [61]. Using metric (4), the field Eqs. (2) and (3) reduce to

$$\frac{3}{4\omega}\phi^2\left(H^2+\frac{k}{a^2}\right)-\frac{1}{2}\dot\phi^2+\frac{3}{2\omega}H\dot\phi\phi=\rho_m+\rho_D, \tag{5}$$

$$\frac{-1}{4\omega}\phi^2\left(2\frac{\ddot a}{a}+H^2+\frac{k}{a^2}\right)-\frac{1}{\omega}H\dot\phi\phi-\frac{1}{2\omega}\ddot\phi\phi-\frac{1}{2}\left(1+\frac{1}{\omega}\right)\dot\phi^2 =p_D, \tag{6}$$

$$\ddot\phi+3H\dot\phi-\frac{3}{2\omega}\left(\frac{\ddot a}{a}+H^2+\frac{k}{a^2}\right)\phi=0, \tag{7}$$

where $H=\dot a/a$ is the Hubble parameter, ρ_D and p_D are, respectively, the energy density and pressure of DE, and ρ_m is the pressureless matter density which contains both dark matter (DM) and baryonic matter (BM) densities i.e. $\rho_m=\rho_c+\rho_b$ where ρ_c and ρ_b are the energy densities of dark matter and baryonic matter respectively.

To be more general and because of some observational evidences [62,63], here we propose the case where there is an interaction between GDE and DM. In this case the semi-conservation equations read

$$\dot\rho_D+3H\rho_D(1+w_D)=-Q, \tag{8}$$

$$\dot\rho_c+3H\rho_c=Q, \tag{9}$$

$$\dot\rho_b+3H\rho_b=0, \tag{10}$$

where Q represents the interaction term between dark matter and dark energy and here we assume that the baryonic matter is conserved separately. We assume $Q=3\xi H(\rho_m+\rho_D)$ with ξ being a constant. Such a choice for interacting term implies the DE and DM component do not conserve separately while the total density is still conserved through

$$\dot\rho+3H(\rho+P)=0, \tag{11}$$

where $\rho=\rho_D+\rho_m$ and $P=P_D$.

The ghost energy density is proportional to the Hubble parameter [31]

$$\rho_D=\alpha H, \tag{12}$$

where $\alpha>0$ is roughly of order Λ^3_{QCD} and Λ_{QCD} are QCD mass scale. Taking into account the fact that $\Lambda_{QCD}\sim 100$ MeV and $H\sim 10^{-33}$ eV for the present time, this gives the right order of magnitude $\rho_D\sim(3\times10^{-3}\ \text{eV})^4$ for the ghost energy density [31].

Since the system of Eqs. (5)–(7) is not closed, we still have another degree of freedom in analyzing the set of equations. As usual we assume the BD scalar field ϕ has a power law relation versus the scale factor,

$$\phi=\phi_0 a(t)^\varepsilon. \tag{13}$$

An interesting case is when ε is small whereas ω is high so that the product $\varepsilon\omega$ results of order unity [64,65]. In Section 4 we will consider the $\omega\varepsilon=1$ condition for constraining the model by observational data. This is interesting because local astronomical experiments set a very high lower bound on ω [66]; in particular, the Cassini experiment implies that $\omega>10^4$ [46,48]. Now we take the time derivative of relation (13). We arrive at

$$\frac{\dot\phi}{\phi}=\varepsilon\frac{\dot a}{a}=\varepsilon H. \tag{14}$$

Combining Eqs. (13) and (14) with the first Friedmann equation (5), we get

$$H^2\left(1-\frac{2\omega}{3}\varepsilon^2+2\varepsilon\right)+\frac{k}{a^2}=\frac{4\omega}{3\phi^2}(\rho_D+\rho_m). \tag{15}$$

As usual the fractional energy densities are defined as

$$\Omega_c=\frac{\rho_c}{\rho_{cr}}=\frac{4\omega\rho_c}{3\phi^2H^2}, \tag{16}$$

$$\Omega_b=\frac{\rho_b}{\rho_{cr}}=\frac{4\omega\rho_b}{3\phi^2H^2}, \tag{17}$$

$$\Omega_k=\frac{\rho_k}{\rho_{cr}}=\frac{k}{H^2a^2}, \tag{18}$$

$$\Omega_D=\frac{\rho_D}{\rho_{cr}}=\frac{4\omega\rho_D}{3\phi^2H^2}, \tag{19}$$