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Constraint on the generalized Chaplygin gas as an unified dark fluid model after Planck 2015

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ABSTRACT

The generalized Chaplygin gas could be considered as the unified dark fluid model because it might describe the past decelerating matter dominated era and at present time it provides an accelerating expansion of the Universe. In this paper, we employed the Planck 2015 cosmic microwave background anisotropy, type-Ia supernovae, observed Hubble parameter data sets to measure the full parameter space of the generalized Chaplygin gas as an unified dark matter and dark energy model. The model parameters B_s and α determine the evolutional history of this unified dark fluid model by influencing the energy density $\rho_{GCG} = \rho_{GCG0}[B_s + (1 - B_s)a^{-3(1+\alpha)}]^{1/(1+\alpha)}$. We assume the pure adiabatic perturbation of unified generalized Chaplygin gas. In the light of Markov Chain Monte Carlo method, we found that $B_s = 0.759^{+0.020+0.051}_{-0.032-0.046}$ and $\alpha = 0.0801^{+0.0208+0.1087}_{-0.0801-0.0801}$ at 2σ level. The model parameter α is very close to zero, the nature of GCG model is very similar to cosmological standard model ΛCDM.

1. Introduction

In modern cosmology, Many theoretical models have been used to explain the current accelerating expansion [1]. Accelerating expansion of the Universe has been shown from the type Ia supernova (SNIa) observations [2,3] in 1998. During these years from that time, some other and updated observational results, including current Cosmic Microwave Background (CMB) anisotropy measurement from Planck 2015 [4–6], and the updated SNIa data sets from the Joint Light-curve Analysis (JLA) sample [7], also strongly support the present acceleration of the Universe. The latest release of Planck 2015 full-sky maps about the CMB anisotropies [6] indicates that baryon matter component is about 4% for total energy density, and about 96% energy density in the Universe is invisible which includes dark energy and dark matter. Considering the four-dimensional standard cosmology, this accelerated expansion for universe predict that dark energy (DE) as an exotic component with negative pressure is filled in the Universe. And it is shown that DE takes up about two-thirds of the total energy density from cosmic observations. The remaining one third is dark matter (DM). In theory, amount of DE models have already been constructed, for the reviews and papers please see [1,8–17]. However there exists another possibility that the invisible energy component is a unified dark fluid. i.e. a mixture of dark matter and dark energy.

If one treats the dark energy and dark matter as an unified dark fluid, the corresponding models have been put forward and studied in Refs. [18–32]. In these unified dark fluid models, the Chaplygin gas (CG) and its generalized model have been widely studied in order to explain the accelerating universe [21–28]. The most interesting property for this scenario is that, two unknown dark sections—dark energy and dark matter can be unified by using an exotic equation of state. The original Chaplygin gas model can be obtained from the string Nambu–Goto action in the light cone coordinate [33]. For generalized Chaplygin gas (GCG), it emerges as an effective fluid of a generalized dbrane in a $(d + 1, 1)$ space time, and its action can be written as a generalized Born–Infeld form [23]. Considering that the application of string theory in principle is in very high energy when the quantum effects is important in early universe [33]. The generalized Chaplygin gas (GCG) model is characterized by two model parameters B_s and α, which could be determined by the cosmic observational data sets. In order to constrain the model parameter space of GCG model, Xu [26] treated the dark energy and dark matter as a whole energy component, performed a global fitting on GCG model by the Markov Chain Monte Carlo (MCMC) method by the observational data sets CMB from WMAP-seven-year [34], BAO [35], SNIa from Union2 [36] data. The tight constraint had been obtained: $\alpha = 0.00126^{+0.000970+0.00268}_{-0.00126-0.00126}$ and $B_s = 0.775^{+0.0161+0.0307}_{-0.0161-0.0338}$ at 2σ level. For the very small values of GCG parameter α, it was concluded that GCG is very close to ΛCDM model. Amendola et al. [15] adopted the WMAP-first-year temperature power spectra [37] and SNIa data [2,3] to test the GCG model parameter space, and it was also concluded that GCG is very close to ΛCDM model. So in the light of previous reference, we will test the parameter space of GCG model with the recently released data sets, CMB from Planck 2015 [4–6], SNIa from JLA sample [7],

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and the observed Hubble parameter data [38], it is worthwhile to anticipate that a different constraint will be obtained.

In this paper, the outline is as follows. In Section 2, we would show the background and perturbation equations of GCG model when the pure adiabatic contribution has been considered. In Section 3, based on the MCMC method, the global fitting results of GCG model parameters would be obtained by the joint observational data sets. Then, we might make some analysis on the measurement results. The conclusion would be drawn in the last section.

2. The background and perturbation equations of generalized Chaplygin gas model

The GCG fluid is treated as an unified component in the Universe, its equation of state reads

$$p_{GCG} = -A/\rho_{GCG}^{\alpha} \tag{1}$$

where A and α are model parameters.

By adopting the continuity equation, one could calculate the energy density of GCG fluid as

$$\rho_{GCG} = \rho_{GCG0}\left[B_s + (1 - B_s)a^{-3(1+\alpha)}\right]^{\frac{1}{1+\alpha}} \tag{2}$$

where $B_s = A/\rho_{GCG0}^{1+\alpha}$ and α are the model parameters which could be constrained by the observational data sets. The parameter condition $0 \leq B_s \leq 1$ is required to keep the positive energy density. When $\alpha = 0$ in Eq. (2), we easily get the cosmological standard model ΛCDM; if $\alpha = 1$ the CG model might be obtained. The equation of state of GCG is

$$w = -\frac{B_s}{B_s + (1 - B_s)a^{-3(1+\alpha)}}. \tag{3}$$

where w is non-positive from the above equation.

In the flat Universe, one has the Friedmann equation

$$H^2 = H_0^2\left\{(1 - \Omega_b - \Omega_r)\left[B_s + (1 - B_s)a^{-3(1+\alpha)}\right]^{\frac{1}{1+\alpha}} + \Omega_b a^{-3} + \Omega_r a^{-4}\right\} \tag{4}$$

where H and H_0 are the Hubble parameter and its present value, Ω_b and Ω_r are dimensionless energy density parameters of baryon and radiation.

In Ref. [21], the author firstly studied the perturbation evolution of GCG fluid in order to explore the effects on the CMB anisotropic power spectra, sand then in Ref. [26], the author made a similar perturbation analysis by the assumption of pure adiabatic contribution. Under the pure adiabatic perturbation mode, the sound speed of GCG is

$$c_s^2 = \frac{\delta p}{\delta \rho} = \frac{\dot{p}}{\dot{\rho}} = -\alpha w, \tag{5}$$

due to the non-positivity of equation of state w, $\alpha \geq 0$ is required to keep the non-negativity of sound speed, and the positive α is necessary for the stability of GCG perturbations [26], and the reasonable range is $0 \leq \alpha \leq 1$ from the detailed analysis in Refs. [21,39], when α is negative, the GCG model would possibly undergo catastrophic instabilities due to an imaginary speed of sound.

According to the conservation of energy–momentum tensor $T^{\mu}_{\nu;\mu} = 0$, ignoring the shear perturbation, one could the deduce the perturbation equations of density contrast and velocity divergence for GCG [26]

$$\dot{\delta}_{GCG} = -(1 + w)(\theta_{GCG} + \frac{\dot{h}}{2}) - 3\mathcal{H}(c_s^2 - w)\delta_{GCG} \tag{6}$$

$$\dot{\theta}_{GCG} = -\mathcal{H}(1 - 3c_s^2)\theta_{GCG} + \frac{c_s^2}{1 + w}k^2\delta_{GCG} \tag{7}$$

where the dot denotes the derivative of conformal time, the notations follow Ma and Bertschinger [40]. In our calculation, the adiabatic initial conditions are used.

3. Observational data sets and methodology

In this section we first describe the astronomical data with the statistical technique to constrain the GCG scenarios and the results of the analyses. We include the following sets of astronomical data.

- CMB: We use CMB data from the Planck 2015 measurements [4,5], where we combine the full likelihoods C_l^{TT}, C_l^{EE}, C_l^{TE} in addition with low$-l$ polarization $C_l^{TE} + C_l^{EE} + C_l^{BB}$, which notationally is same with "PlanckTT, TE, EE + lowP" of Ref. [5].
- JLA: This is the Supernovae Type Ia sample that contains 740 data points spread in the redshift interval $z \in [0.01, 1.30]$ [7]. This low redshifts sample is the first indication for an accelerating universe.
- *Cosmic Chronometers (CC):* The Hubble parameter measurements from most old and passively evolving galaxies, known as cosmic chronometers (CC) have been considered to be potential candidates to probe the nature of dark energy due to their model-independent measurements. For a detailed description on how one can measure the Hubble parameter values at different redshifts through this CC approach, and its usefulness, we refer to [38]. Here, we use 30 measurements of the Hubble parameter at different redshifts within the range $0 < z < 2$.

So the total likelihood χ^2 can be constructed as

$$\chi^2 = \chi^2_{CMB} + \chi^2_{JLA} + \chi^2_{CC}. \tag{8}$$

In order to extract the observational constraints of the GCG scenarios, we use the publicly available Monte Carlo Markov Chain (MCMC) package COSMOMC [41] equipped with a convergence diagnostic followed by the Gelman and Rubin statistics, which includes the CAMB code [42] to calculate the CMB power spectra. We modified this code for the GCG model with the perturbation of unified dark fluid. We have used the following 7-dimensional parameter space

$$P \equiv \{\omega_b, 100\theta_{MC}, \tau, \alpha, B_s, n_s, \log[10^{10}A_s]\} \tag{9}$$

where $\Omega_b h^2$ stands for the density of the baryons and dark matter, $100\theta_{MC}$ refers to the ratio of sound horizon and angular diameter distance, τ indicates the optical depth, α and B_s are two added parameters of GCG model, n_s is the scalar spectral index, and A_s represents the amplitude of the initial power spectra. The pivot scale of the initial scalar power spectra $k_{s0} = 0.05$ Mpc^{-1} is used. A positive parameter α is required to keep the non-negativity of sound speed, and the positive α is necessary for the stability of GCG perturbations according to the analysis of Ref. [26], thus, $\alpha \geq 0$ is a compulsory condition for the observational constraint of GCG model. During the MCMC analysis, we generally fix some priors on the model parameters. Here, we show the priors set on various cosmological parameters, we take the following priors to model parameters: $\Omega_b h^2 \in [0.005, 0.1]$, $\Theta_S \in [0.5, 10]$, $\tau \in [0.01, 0.8]$, $\alpha \in [0, 1]$, $B_s \in [0, 1]$, $n_s \in [0.5, 1.5]$ and $\log[10^{10}A_s] \in [2.7, 4]$.

4. Analysis on the fitting results

Let us summarize the main observational results extracted from the GCG unified model by using the three different combined observational data, CMB+CC, CMB+JLA, CMB+JLA+CC, described in the above section. In Table 1 we summarize the main results of global fitting results, at the first sight, the combination CMB+CC