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Comparing the VGCG model as the unification of dark sectors with observations

LU JianBo[1*], CHEN LiDong[2], XU LiXin[3] & LI TianQiang[1]

[1] *Department of Physics, Liaoning Normal University, Dalian 116029, China;*
[2] *Jilin Radio and TV University, Jilin 130022, China;*
[3] *School of Physics and Optoelectronic Technology, Dalian University of Technology, Dalian 116024, China*

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Current observations indicate that 95% of the energy density in the universe is the unknown dark component. The dark component is considered composed of two fluids: dark matter and dark energy. Or it is a mixture of these two dark components, i.e., one can consider it an exotic unknown dark fluid. With this consideration, the variable generalized Chaplygin gas (VGCG) model is studied with not dividing the unknown fluid into dark matter and dark energy parts in this paper. By using the Markov Chain Monte Carlo method, the VGCG model as the unification of dark sectors is constrained, and the constraint results on the VGCG model parameters are, $n = 0.00057^{+0.0001+0.0009}_{-0.0006-0.0006}$, $\alpha = 0.0015^{+0.0003+0.0017}_{-0.0015-0.0015}$ and $B_s = 0.778^{+0.016+0.030}_{-0.016-0.035}$, obtained by the cosmic microwave background data from the 7-year WMAP full data points, the baryon acoustic oscillation data from Sloan Digital Sky Survey (SDSS) and 2-degree Field Galaxy Redshift (2dFGRS) survey, and the Union2 type Ia supernova data with systematic errors. At last, according to the evolution of deceleration parameter it is shown that an expanded universe from deceleration to acceleration can be obtained in VGCG cosmology.

variable generalized Chaplygin gas (VGCG), unification of dark matter and dark energy, cosmic constraints

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1 Introduction

The recent cosmic observations, such as the type Ia supernovae (SNIa) [1], the cosmic microwave background (CMB) [2] and the clusters of galaxies [3], indicate that: (1) the expansion of present universe is speeding up rather than slowing down. This acceleration is not consistent with the standard cosmology, and there seems to be a special matter with the negative pressure in the universe; (2) the baryon matter component is about 5% taking up the total energy density, and about 95% energy density (called dark component) in the universe is invisible. Several hypotheses about the dark component have been investigated. The most popular view is that the dark component includes dark matter and dark energy, and they are not correlative. The latter is deemed responsible for the accelerating universe. These two dark sectors are considered not independent, but with interactions between them [4–10]. Still, one can come up with other possibilities about the dark component by presenting interesting scenarios. With this consideration, we study a unified fluid to explain the accelerating universe in this paper, i.e., we consider the unknown dark component as a mixture, instead of dividing it into two dark sectors.

It is well known that the Chaplygin gas (CG) [11] as an original unified model of dark matter and dark energy, is almost ruled out by the current observational data. So, several extended Chaplygin gas (ECG) models are constructed

*Corresponding author (email: lvjianbo819@163.com)

and widely studied for interpreting the accelerating universe, such as the variable Chaplygin gas (VCG) [12], the generalized Chaplygin gas (GCG) [13] model and so forth [14,15]. In these scenarios, the most interesting property is that the dark component in universe can be unified to an exotic equation of state, since these CG fluids behave as dust at early stage and as dark energy at later stage. One knows the GCG Lagrangian density can be expressed as a generalized Born-Infeld form [13], $\mathcal{L}_{\rm GBI}=-A^{\frac{1}{1+\alpha}}[1-(g^{\mu\nu}\theta_{,\mu}\theta_{,\nu})^{\frac{1+\alpha}{2\alpha}}]^{\frac{\alpha}{1+\alpha}}$, which reduces to the Born-Infeld Lagrangian for $\alpha=1$. It can be found that the observational constraint on above two ECG models: VCG [16] and GCG [17,18] have been studied. In this paper, we discuss a generalized form related to the GCG model, i.e., the variable generalized Chaplygin gas (VGCG) model. We apply the full cosmic microwave background (CMB) data from 7-year WMAP [19], the baryon acoustic oscillations (BAO) data from Sloan Digital Sky Survey (SDSS) and 2-degree Field Galaxy Redshift Survey (2dFGRS) survey [20], and the 557 Union2 dataset of type supernovae Ia (SNIa) [21] with systematic errors, to constrain this model. According to the constraint results on model parameter, the evolution of deceleration parameter is discussed.

The paper is organized as follows. In sect. 2, the VGCG model as the unification of dark sectors is introduced briefly. Sect. 3 presents the method of data analysis, and constrain the VGCG model parameters. Sect. 4 shows the evolution of deceleration parameter in this unified model. Sect. 5 is the conclusions.

2 Variable generalized Chaplygin gas as the unification of dark sectors

The generalized Chaplygin gas (GCG) unified model is expressed by the equation of state,

$$p_{\rm GCG}=-\frac{A}{\rho^{\alpha}_{\rm GCG}},\tag{1}$$

where A and α are two constant parameters, $p_{\rm GCG}$ and $\rho_{\rm GCG}$ are pressure and energy density of GCG fluid, respectively. We consider the parameter A in GCG model is not a constant, but a power-law function with respect to cosmic scale factor: $A(a)=A_0a^{-n}$. This extended form is called VGCG model. Then for VGCG background fluid it has a relation between the energy density $\rho_{\rm VGCG}$ and the pressure $p_{\rm VGCG}$

$$p_{\rm VGCG}=-\frac{A_0a^{-n}}{\rho^{\alpha}_{\rm VGCG}},\tag{2}$$

where A_0, n and α are parameters in the model. For $n=0$, this model reduces to the GCG scenario. By using the energy conservation equation: $d(\rho a^3)=-pd(a^3)$, the energy density of VGCG can be derived as

$$\rho_{\rm VGCG}=\rho_{\rm 0VGCG}\left[B_{\rm s}a^{-n}+(1-B_{\rm s})a^{-3(1+\alpha)}\right]^{\frac{1}{1+\alpha}},\tag{3}$$

where $B_{\rm s}=\frac{3(1+\alpha)}{3(1+\alpha)-n}\frac{A_0}{\rho^{1+\alpha}_{\rm 0VGCG}}$. For an expanding universe, there should be $n>0$ and $3(1+\alpha)>0$. If they are negative, $a\to\infty$ implies $\rho\to\infty$, which is not the real universe. Considering spatially flat Friedmann-Robertson-Walker universe with including baryon matter $\rho_{\rm b}$, radiation matter $\rho_{\rm r}$ and VGCG fluid $\rho_{\rm VGCG}$, according to the Friedmann equation the Hubble parameter H can be written as

$$\begin{aligned}H^2(a)&=H_0^2E^2(a)\\&=H_0^2\Big\{\Omega_{\rm 0VGCG}\Big[B_{\rm s}a^{-n}+(1-B_{\rm s})a^{-3(1+\alpha)}\Big]^{\frac{1}{1+\alpha}}\\&\quad+\Omega_{\rm 0b}a^{-3}+\Omega_{\rm 0r}a^{-4}\Big\}\end{aligned}\tag{4}$$

with $\Omega_{\rm 0VGCG}=1-\Omega_{\rm 0b}-\Omega_{\rm 0r}$, where H_0 is the current value of the Hubble parameter, Ω_{0i} denotes the current values of dimensionless energy density for baryon, radiation and VGCG fluid, respectively. One knows that in the unified model of dark sectors the different decomposition manner is used for dark components, the different cosmic constraint results will be given. And also, it is not easy to divide the VGCG fluid into dark matter and dark energy in the most reasonable manner. So, here we investigate the cosmic constraints on VGCG model as the unification of dark sectors, i.e., the solely dark matter or dark energy component does not appear.

Next we show the perturbation evolution equations in VGCG unified model of dark sectors. In the synchronous gauge, using the conservation of energy-momentum tensor $T^{\mu}_{\nu;\mu}=0$, one has the perturbation equations of density contrast $\delta_{\rm VGCG}$ and velocity divergence $\theta_{\rm VGCG}$ for VGCG

$$\begin{aligned}\dot{\delta}_{\rm VGCG}&=-(1+w_{\rm VGCG})\left(\theta_{\rm VGCG}+\frac{\dot{h}}{2}\right)\\&\quad-3\mathcal{H}(c_{\rm s}^2-w_{\rm VGCG})\delta_{\rm VGCG},\end{aligned}\tag{5}$$

$$\begin{aligned}\dot{\theta}_{\rm VGCG}&=-\mathcal{H}(1-3c_{\rm s}^2)\theta_{\rm VGCG}\\&\quad+\frac{c_{\rm s}^2}{1+w_{\rm VGCG}}k^2\delta_{\rm VGCG}-k^2\sigma_{\rm VGCG},\end{aligned}\tag{6}$$

following the notation of Ma and Bertschinger [22]. Thereinto, $\mathcal{H}$ is the Hubble parameter defined by the conformal time, $h\equiv h_{ii}$ is the trace part in the synchronous metric perturbation h_{ij}, k is the wavenumber of Fourier mode, $c_{\rm s}^2$ denotes the adiabatic squared sound speed, $w\equiv p/\rho$ denotes the state parameter, and σ shows the shear perturbation. Concretely, the shear perturbation $\sigma_{\rm VGCG}=0$ is assumed and the adiabatic initial conditions are adopted in our calculation; with assumption of pure adiabatic contribution to the perturbations, the adiabatic squared sound speed for VGCG fluid is expressed as,

$$\begin{aligned}c_{\rm s}^2&=\frac{\partial p_{\rm VGCG}}{\partial\rho_{\rm VGCG}}=w_{\rm VGCG}-\frac{\dot{w}_{\rm VGCG}}{3\mathcal{H}(1+w_{\rm VGCG})}\\&=\frac{-(1+\alpha)(3+3\alpha-n)nB_{\rm s}a^{-n}}{(3+3\alpha)[nB_{\rm s}a^{-n}+3(1+\alpha)(1-B_{\rm s})a^{-3(1+\alpha)}]}\\&\quad+\frac{(3+3\alpha-n)\alpha B_{\rm s}a^{-1-n}}{(3+3\alpha)[B_{\rm s}a^{-n}+(1-B_{\rm s})a^{-3(1+\alpha)}]},\end{aligned}\tag{7}$$

where "dot" denotes the derivative relative to conformal time t; and for VGCG fluid the state parameter $w_{\rm VGCG}$ as a function of scale factor a can be described as

$$w_{\rm VGCG} \equiv \frac{p_{\rm VGCG}}{\rho_{\rm VGCG}} = \frac{[-1+\frac{n}{3(1+\alpha)}]B_s a^{-n}}{B_s a^{-n}+(1-B_s)a^{-3(1+\alpha)}}. \quad (8)$$

For the perturbation theory in gauge ready formalism, please see ref. [23].

3 Data fitting and discussion on VGCG unified model of dark sectors

3.1 Method and data points

In the following we apply the Markov Chain Monte Carlo (MCMC) method to investigate the global constraints on parameter space in above VGCG unified model. The MCMC code is based on the publicly available CosmoMC package [24] including the CAMB [25] code. We modified the code for the VGCG model as a unified fluid of dark sectors with its perturbations included. The following 8-dimensional parameter space is adopted

$$P \equiv \{\omega_b, \Theta_S, \tau, n_s, \log[10^{10}A_s], B_s, \alpha, n\}, \quad (9)$$

where $\omega_b = \Omega_{0b}h^2$ is the physical baryon density, Θ_S (multiplied by 100) is the ration of the sound horizon and angular diameter distance, τ is the optical depth, n_s is the scalar spectral index, A_s is the amplitude of the initial power spectrum, B_s, α and n are three newly added model parameters related to VGCG. The pivot scale of the initial scalar power spectrum $k_{s0} = 0.05$ Mpc^{-1} is used. We take the following priors to model parameters: $\omega_b \in [0.005, 0.1]$, $\Theta_S \in [0.5, 10]$, $\tau \in [0.01, 0.8]$, $n_s \in [0.5, 1.5]$, $\log[10^{10}A_s] \in [2.7, 4]$, $B_s \in [0, 1]$, $\alpha \in [-1, 1]$, and $n \in [0, 10]$. In addition, the hard coded prior on the comic age 10 Gyr $< t_0 <$ 20 Gyr is imposed. Also, the weak Gaussian prior on the physical baryon density $\omega_b = 0.022 \pm 0.002$ [26] from big bang nucleosynthesis and Hubble constant $H_0 = (74.2 \pm 3.6)$ kms^{-1}Mpc^{-1} [27] are adopted.

The total likelihood $\mathcal{L} \propto e^{-\chi^2/2}$ is calculated to get the distribution, here χ^2 is given as

$$\chi^2 = \chi^2_{\rm CMB} + \chi^2_{\rm BAO} + \chi^2_{\rm SNIa}. \quad (10)$$

The CMB data include temperature and polarization power spectrum from WMAP 7-year full data points [19] as dynamic constraint. The geometric constraint comes from standard ruler BAO and standard candle SNIa. For BAO data, the values: $\{r_s(z_d)/D_V(z = 0.2), r_s(z_d)/D_V(z = 0.5)\}$ and their inverse covariant matrix [20] are used. The detailed descriptions of BAO constraint method, please see refs. [28,29]. The 557 SNIa Union2 data with systematic errors are also included [21]. For the detailed description of SNIa, please see refs. [30–36]. For fitting this model to above CMB+BAO+SNIa data, the redshift at drag epoch z_d depending on the calculation of dark matter density is recalculated numerically as shown in ref. [29], since the usually used fitting formula given by ref. [37] is only valid for the case that the baryon matter and the dark matter scaling $\rho_b \propto a^{-3}$ and $\rho_{\rm dm} \propto a^{-3}$ are respected. Obviously, this fitting formula is not feasible in our calculation.

3.2 Cosmic constraints on VGCG dark model

By using above combined datasets, we get the constraint results on cosmological parameters in VGCG unified model of dark sectors. For easy to see, the contours of VGCG model parameters are shown in Figure 1, and the calculation results on these parameters with their confidence levels are listed in Table 1. From this table we can see that the value of parameter n with the confidence levels is near to zero, i.e., it is indicated that the VGCG model tends to reduce to GCG model. Since the value of parameter n is much little in VGCG model, the evolution of squared sound speed c_s^2, the evolution of state parameter $w_{\rm VGCG}$, and the CMB C_l^{TT} power spectrum in this model are very similar to the cases of GCG unified model as shown in ref. [29], so we do not discuss these quantities in VGCG dark model. At last, we list the constraint values of some other cosmological parameters in VGCG cosmology: $\tau = 0.0900^{+0.0070+0.0249}_{-0.0076-0.0241}$, $\theta = 1.0488^{+0.0025+0.0051}_{-0.0025-0.0051}$, $z_{\rm re} = 10.534^{+1.219+2.307}_{-1.251-2.368}$, $n_s = 0.9904^{+0.016+0.0319}_{-0.016-0.0302}$, $\log[10^{10}A_s] = 3.0877^{+0.0354+0.0700}_{-0.0361-0.0687}$ and Age= $13.660^{+0.113+0.223}_{-0.113-0.221}$, whose contours are plotted in Figure 2.

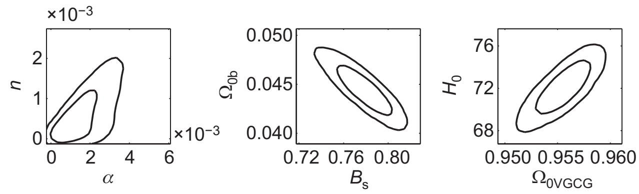

Figure 1 The contours of VGCG model parameters.

Table 1 The 1σ and 2σ confidence levels of VGCG model parameters

Parameters	Mean values with confidence levels
Ω_b	$0.0445^{+0.0016+0.0035}_{-0.0017-0.0032}$
$\Omega_{\rm 0VGCG}$	$0.9555^{+0.0015+0.0031}_{-0.0017-0.0036}$
n	$0.00057^{+0.0001+0.0009}_{-0.0006-0.0006}$
α	$0.0015^{+0.0003+0.0017}_{-0.0015-0.0015}$
B_s	$0.778^{+0.016+0.030}_{-0.016-0.035}$
H_0	$72.034^{+1.620+3.182}_{-1.576-3.203}$

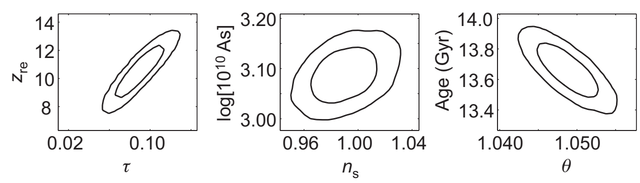

Figure 2 The contours of cosmological parameters in flat VGCG cosmology.

Further, comparing with ref. [38], it is found that the VGCG model in our paper is consistent with the NGCG (new generalized Chaplygin gas) model introduced in ref. [38], since they have the same equation of state, $p = -A(a)/\rho^{\alpha}$. Though the required form of function $A(a) = -w_x A a^{-3(1+w_x)(1+\alpha)}$ in ref. [38] is different from our case, they are equivalent to each other with redefining model parameters by relations: $B_s = \frac{\Omega_{0x}}{1-\Omega_{0b}}$, $\alpha = \eta - 1$ and $n = 3(1 + w_x)(1 + \alpha)$. The constraint results on NGCG model parameters in ref. [38] at 1σ confidence level are $w_x = -0.98^{+0.15}_{-0.20}$ and $\eta = 1.06^{+0.20}_{-0.16}$, where the used data include 157 SNIa data, the value of dimensionless parameter $A = 0.469 \pm 0.017$ for BAO observation and the value of shift parameter $R = 1.716 \pm 0.062$ for CMB observation. Equivalently, with the relations: $\alpha = \eta - 1$ and $n = 3(1 + w_x)(1 + \alpha)$, the values of α and n indicated by ref. [38] at 1σ confidence level are $\alpha = 0.06^{+0.20}_{-0.16}$ and $n = 0.064^{+0.477}_{-0.636}$ (since the constraints on the dimensionless energy density of separated dark components in ref. [38] are not discussed, the corresponding parameter B_s can not be calculated). From these constraint results, one can see that the confidence levels of parameters α and n given by ref. [38] are larger than our results, and our constraint results on model parameters for the undivided VGCG unified fluid are included in these results. In addition, one knows that for the NGCG fluid it indicates there are the interaction between dark matter and dark energy according to the analysis of the energy density for dark components [38]. Considering the consistency between VGCG and NGCG model, it is shown that the VGCG model is also equivalent to a coupling between dark components, as shown in refs. [39–45]. Also, this coupling behavior is consistent with the undivided operation for VGCG fluid in our paper.

4 The evolutions of deceleration parameter in VGCG cosmology

According to eq. (4) and using the relation $z = \frac{1-a}{a}$, deceleration parameter q can be expressed as a function of redshift z,

$$q = (1+z)\frac{1}{H}\frac{\mathrm{d}H}{\mathrm{d}z} - 1 = \frac{1}{2} + \frac{3}{2}B_s\Big[-1 + \frac{n}{3(1+\alpha)}\Big](1+z)^n \times(1-\Omega_{0b})\Big[B_s(1+z)^n + (1-B_s)(1+z)^{3(1+\alpha)}\Big]^{\frac{-\alpha}{1+\alpha}} \times\Big\{(1-\Omega_{0b})\Big[B_s(1+z)^n + (1-B_s)(1+z)^{3(1+\alpha)}\Big]^{\frac{1}{1+\alpha}} + \Omega_{0b}(1+z)^3\Big\}^{-1}. \quad (11)$$

The evolution of deceleration parameter with its confidence level is plotted in Figure 3. From this figure, it is easy to see that the expanded universe from deceleration to acceleration is obtained. Furthermore, according to the evolution of this parameter in Figure 3 we can also obtain the values of current deceleration parameter $q_0 = -0.615^{+0.214}_{-0.214}$, and transition redshift $z_T = 0.795^{+0.049}_{-0.049}$.

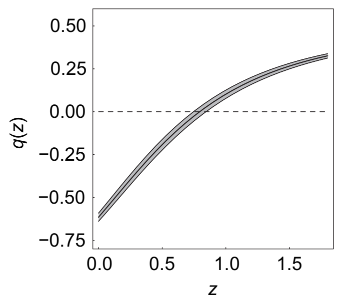

Figure 3 The evolution of deceleration parameter with its confidence level in flat VGCG cosmology.

5 Conclusion

In this paper we apply the recently observational data including the full CMB data points from 7-year WMAP, the BAO data from SDSS and 2dFGRS survey, and the SNIa Union2 data to constrain the VGCG unified model of dark sectors. Here we do not divide this unknown fluid into two dark components. According to the constraint results on model parameters, it is indicated that the VGCG model tends to reduce to the GCG model, for the value of parameter n is near to zero. Further, considering that the value of parameter α also do not depart from zero much it is shown that the VGCG practically coincides with the ΛCDM model (i.e., cosmological constant dark energy model). In addition, comparing with ref. [38] it is found that the more stringent constraints on VGCG model parameters are given in this paper, and the undivided VGCG fluid is equivalent to the coupling models between dark matter and dark energy. At last, we discuss the evolution of deceleration parameter in VGCG cosmology, and it is found that an expanded universe from deceleration to acceleration can be obtained.

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