Spatial Ricci scalar dark energy model

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Inspired by holographic principle, we suggest that the density of dark energy is proportional to the spatial Ricci scalar curvature (SRDE). Such model is phenomenologically viable. The best fit values of its parameters at 68% confidence level are found to be: Ω_m0 = 0.259±0.016 and α = 0.261±0.0122, constrained from the Union+CF A3 sample of 397 SNIa and the BAO measurement. We find the equation of state of SRDE crosses −1 at z ≃ −0.14. The present values of the deceleration parameter q(z) for SRDE is found to be q_0 ≃ −0.85. The phase transition from deceleration to acceleration of the Universe for SRDE occurs at the redshift z_0 ≃ 0.4. After studying on the perturbation of each component of the Universe, we show that the matter power spectra and cosmic microwave background temperature anisotropy is slightly affected by SRDE, compared with ΛCDM.

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I. INTRODUCTION

In the last decade a convergence of independent cosmological observations suggested that the Universe is experiencing accelerated expansion. An unknown energy component, dubbed as dark energy, may be responsible for this phenomenon. Numerous dynamical dark energy models have been proposed in the literature, such as quintessence [1, 2], phantom [3, 4], k-essence [7–10], tachyon [11–14], DGP [15, 16], Chaplygin gas [17–19], ect. However, the simplest and most theoretically appealing candidate of dark energy is the vacuum energy (or the cosmological constant Λ) with a constant equation of state (EoS) parameter w = −1. This scenario is in general agreement with the current astronomical observations, but has difficulties to reconcile the small observational value of dark energy density with estimates from quantum field theories; this is the cosmological constant problem (see e.g. [20–23]). Recently it was shown that ΛCDM model may also suffer from an age problem [24]. According to the holographic principle [25], a method may help solve this problem was proposed that an unknown vacuum energy with density proportional to the Hubble scale, Λ ∝ l^2 ∼ H^2, could be present [26–28], here l is a characteristic length. Unfortunately, the EoS for such vacuum energy is zero and the Universe is decelerating. Alternatively, the particle horizon can be introduced as the characteristic length l. However, the EoS is greater than −1/3 in this case; so it still could not explain the observed acceleration of the Universe [29–32]. In view of this, the future event horizon was proposed as the characteristic length l. This holographic dark energy model and its interacting version are successful in fitting the current observations [33–44]. However, this holographic dark energy model has suffered some serious conceptual problems. Firstly, the present value of dark energy is determined by the future evolution of the Universe; this poses a challenge to causality. Secondly, the density of dark energy is a local quantity, while the future event horizon is a global concept of space-time. To avoid these short-comes, another possibility is considered: the characteristic length l is given by the average radius of Ricci scalar curvature R^{−1/2}, in other words, the density of dark energy is proportional to the Ricci scalar curvature, ρ_X ∝ R (hereafter RDE for short) [45]. Recent studies on this model see e.g. [46–49]. However, as holographic principle asserting [25], the number of possible states of a region of space is the same as that of binary degrees of freedom distributed on the boundary of the region. To reflect holographic principle more properly, we propose that the density of dark energy is proportional to the spatial Ricci scalar curvature, ρ_X ∝ R_s (hereafter SRDE for short), instead of Ricci scalar curvature. We find SRDE not only has the same properties, but also has properties which RDE doesn’t have.

This paper is organized as follows. In section II, we describe the SRDE model. Observations constraints and cosmic expansion will be discussed in section III. We discuss structure formation in section IV. Finally, conclusions and discussions are made in section V.

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II. SPATIAL RICCI SCALAR DARK ENERGY MODEL

We consider the homogeneous and isotropic Friedmann-Robertson-Walker-Lemaître (FRWL) metric with the scale factor $a(t)$

$$ds^2 = -dt^2 + a^2(t) \left[ \frac{dr^2}{1 - K r^2} + r^2(d\theta^2 + \sin^2 \theta d\phi^2) \right],$$

where the spatial curvature constant $K = +1, 0,$ and $-1$ correspond to a closed, flat and open Universe, respectively. We use the units $c = G = 1$ throughout this study. The Friedmann equations reads

$$H^2 = \frac{8\pi}{3} \sum \rho_i - \frac{K}{a^2},$$

$$\dot{H} = -4\pi \sum (\rho_i + p_i) + \frac{K}{a^2},$$

where $H \equiv \dot{a}/a$ is the Hubble parameter, the dot denotes the derivative with respect to the cosmic time $t$, and the summation runs over the radiation, nonrelativistic matter, and other components. The conservation equation of the $i$th component of energy takes the form

$$\dot{\rho}_i + 3H(\rho_i + p_i) = 0.$$

The spatial Ricci scalar curvature is given by

$$R_s = -\frac{3}{a^2} \left[ \frac{\dot{a}^2}{a} + 2 \left( \frac{\dot{a}}{a} \right)^2 + \frac{2K}{a^2} \right] = -\frac{3}{a^2} \left( \dot{H} + 3H^2 + \frac{2K}{a^2} \right).$$

We assume the density of dark energy component is proportional to the spatial Ricci scalar curvature inspired by the holographic principle

$$\rho_X = -\frac{\alpha}{8\pi} R_s = \frac{3\alpha}{8\pi} \left( \dot{H} + 3H^2 + \frac{2K}{a^2} \right),$$

where $\alpha$ is a constant to be determined. The factor $1/8\pi$ is for convenience in the following calculations. Setting $x = \ln a$, we can rewrite the Friedmann equation (2) as

$$H^2 = \frac{8\pi}{3} \left[ (2\alpha - 1) \frac{3K}{8\pi} e^{-2x} + \rho_{m0} e^{-3x} + \rho_{r0} e^{-4x} \right] + \alpha \left( \frac{1}{2} \frac{dH^2}{dx} + 3H^2 \right),$$

where the $\rho_{m0}$ and $\rho_{r0}$ are the contributions of nonrelativistic matter and radiation (here and thereafter the subscript 0 denotes the value at the present time), respectively. By introducing the scaled Hubble expansion rate $E \equiv H/H_0$, the above Friedmann equation becomes

$$E^2 = (2\alpha - 1)\Omega_{K0} e^{-2x} + \Omega_{m0} e^{-3x} + \Omega_{r0} e^{-4x} + \alpha \left( \frac{1}{2} \frac{dE^2}{dx} + 3E^2 \right),$$

where $\Omega_{K0}$, $\Omega_{m0}$, and $\Omega_{r0}$ are the dimensionless density parameters of the curvature, nonrelativistic matter, and radiation in the present Universe. Solving Eq. (9), we obtain

$$E^2 = -\Omega_{K0} e^{-2x} + \Omega_{m0} e^{-3x} + \Omega_{r0} e^{-4x} + \frac{3\alpha \Omega_{m0}}{2 - 3\alpha} e^{-3x} + \frac{\alpha \Omega_{r0}}{1 - \alpha} e^{-4x} + c_0 e^{(-6+2/\alpha)x}$$

$$= -\Omega_{K0} a^{-2} + \Omega_{m0} a^{-3} + \Omega_{r0} a^{-4} + \frac{3\alpha \Omega_{m0}}{2 - 3\alpha} a^{-3} + \frac{\alpha \Omega_{r0}}{1 - \alpha} a^{-4} + c_0 a^{6+2/\alpha},$$

(9)
where $c_0$ is an integration constant, the density of spatial curvature is defined as $\rho_K = 3K/8\pi a^2$. From the Eq. (9), we obtain the terms come from dark energy.

$$\Omega_X \equiv \rho_X/\rho_c = \frac{3\alpha\Omega_{m0} a^{-3}}{2-3\alpha} + \frac{\alpha\Omega_{r0}}{1-\alpha}a^{-4} + c_0a^{-6+2/\alpha},$$

where $\rho_c$ is the present value of critical energy density. The first term of the right hand of Eq. (10) evolves like radiation, this term can be seen as dark radiation like as in brane dark energy $\cite{54}$. It is interesting nonrelativistic matter, the last term increases with decreasing red shift. While unlike RDE, SRDE also contain one part evolves like radiation, this term can be seen as dark radiation like as in brane dark energy $\cite{54}$. It is interesting the dark radiation also present in Ho\'rava-Lifshitz cosmology $\cite{51,52}$. The equation of state of dark energy reads

$$w_X = -1 - \frac{1}{3} \frac{d\Omega_X}{\Omega_X} = \frac{\alpha\Omega_{r0}}{3(1-\alpha)}a^{-4} + \frac{(1-2\alpha)c_0a^{-6+2/\alpha}}{3\alpha\Omega_{m0} a^{-3} + \alpha\Omega_{r0} a^{-4} + c_0a^{-6+2/\alpha}}$$

For the case of $K = 0$, we obtain $c_0 = 1 - 2\Omega_{m0}/(2 - 3\alpha) - \Omega_{r0}/(1 - \alpha)$ by using $\Omega_{m0} + \Omega_{r0} + \Omega_{X0} = 1$. In next section, we will use this result to constrain the parameters of SRDE model with observational data.

### III. OBSERVATIONAL CONSTRAINTS AND THE EVOLUTION OF THE SRDE

Assuming that the Universe is spatially flat and taking $\Omega_0 = 8 \times 10^{-5}$, we constrain the parameters of SRDE model by using the latest observational data including the Union+CF A3 sample of 397 SNIa and the baryon acoustic oscillation (BAO) measurement from the Sloan Digital Sky Survey (SDSS).

The SNIa data which provide the main evidence for the existence of dark energy in the framework of standard cosmology. Here we consider the latest published 397 Union+CF A3 SNIa data compiled in Table 1 of $\cite{53}$. This dataset add the CFA3 sample to the 307 Union sample $\cite{54}$. Recently, Ref. $\cite{55}$ used these data to study the accelerated expansion of Universe. The resulting theoretical distance modulus $\mu_{th}(z)$ is defined as

$$\mu_{th}(z) = 5\log_{10}D_L(z) + \mu_0,$$

where $\mu_0 = 5\log_{10}h - 42.38$ is the nuisance parameter which can be marginalized over $\cite{56,57}$.

In order to break the degeneracies among the parameters, we consider another observational constraint closely related the measurements of the baryon acoustic oscillation peak in the distribution of SDSS luminous red galaxies (LRG), the $A$ parameter, defined as

$$A \equiv \Omega_{m0}^{1/2}(z_1^2E(z_1))^{-1/3} \left( \int_0^{z_1} dz/E(z) \right)^{2/3}, \quad (13)$$

where $z_1 = 0.35$ is the effective redshift of the LRG sample. The SDSS BAO measurement $\cite{58}$ gives $A_{\text{obs}} = 0.469 (n_s/0.98)^{-0.35} \pm 0.017$, where the scalar spectral index is taken to be $n_s = 0.960$ measured by WMAP5 $\cite{59}$. Note that $A$ is independent of $H_0$, thus these quantities can provide robust constraint as complement to SNIa data on SRDE.

As usual, assuming the measurement errors are Gaussian, the likelihood function is $L \propto e^{-\chi^2/2}$. The model parameters yielding a minimal $\chi^2$ and a maximal $L$ will be favored by the observations. Since the SNIa and BAO are effectively independent measurements, we can simply minimize their total $\chi^2$ value given by

$$\chi^2(\Omega_{m0}, H_0) = \chi^2_{\text{SNIa}} + \chi^2_A,$$

where

$$\chi^2_{\text{SNIa}} = \sum_{i=1}^{N} \frac{(\mu_{\text{obs}}^i(z_i) - \mu_{\text{th}}^i(z_i))^2}{\sigma^2_i}, \quad (15)$$

$$\chi^2_A = \left( \frac{A - A_{\text{obs}}}{\sigma_A} \right)^2, \quad (16)$$

in order to find the best fit values of the parameters of the SRDE. We obtain the best fit values of the parameters at 68% confidence level: $\Omega_{m0} = 0.259 \pm 0.016$ and $\alpha = 0.261 \pm 0.0122$ with $\chi^2_{\text{min}} = 470.007$ (dof= 1.187). For comparing,
we also constrain \( \Lambda \)CDM and RDE with the same data, and find: \( \Omega_{m0} = 0.285 \pm 0.021 \) with \( \chi^2_{\text{min}} = 465.719 \) (dof= 1.173) at 68% confidence level for \( \Lambda \)CDM, \( \Omega_{m0} = 0.274 \pm 0.02 \) and \( \alpha = 0.439 \pm 0.025 \) with \( \chi^2_{\text{min}} = 466.156 \) (dof= 1.174) at 68% confidence level for RDE.

Recently, The best-fit values of parameters of RDE at 68.3% confidence level are constrained to be: \( \Omega_{m0} = 0.324^{+0.024}_{-0.022} \) and \( \alpha = 0.371^{+0.023}_{-0.022} \) corresponding to \( \chi^2_{\text{min}} = 483.130 \), from the latest observational data including the Union+CFA3 sample of 397 SNIa, the shift parameter of the cosmic microwave background given by the five-year WMAP5 observations, and BAO measurement [60].

Figures 1 shows the 68.3%, 95.4% and 99.7% joint confidence contours in the \( \alpha-\Omega_{m0} \) plane for SRDE.

The predicted values of the Hubble parameter \( H \) of the SRDE in 68.3% confidence level limits compared with the observational \( H(z) \) data \([61–63]\) is shown in figure 2; the \( \Lambda \)CDM and RDE cases are also presented for comparison.

Here we take \( H_0 = 72 \text{ kms}^{-1}\text{Mpc}^{-1} \) to calculate the Hubble parameter \( H \) of the SRDE, \( \Lambda \)CDM and RDE.

For \( z \gtrsim 2 \), the EoS parameter of SRDE runs closely to \( -0 \) shown in Fig. 3 meaning the negative pressure of the SRDE dark energy approaches to zero rapidly, compared with the cases of RDE. The EoSs of SRDE and RDE cross \( -1 \) at \( z \simeq 0.14 \), and approach \( w_X \simeq -1.2 \) and \( w_X \simeq -1.05 \) at \( z = 0 \), respectively, consistent with the results obtained recently in Ref. [64]. The properties in SRDE and RDE is interesting and worthy to further study.

In Fig. 4 we plot the evolution of de deceleration parameter,

\[
q = -1 + \frac{1 + z}{E} \frac{dE}{dz}. \tag{17}
\]
FIG. 3: The evolution of the equation of state parameter of SRDE in 68.3% confidence level limits, compared with ΛCDM (the dash line) and RDE (the dash-dot line).

FIG. 4: The deceleration parameter as a function of redshift in 68.3% confidence level limits for SRDE, compared with ΛCDM (the dash line) and RDE (the dash-dot line).

The present values of the deceleration parameter $q(z)$ for SRDE and ΛCDM are found to be $q_{z=0} \sim -0.85$, while $q_{z=0} \sim -0.7$ for RDE. The phase transition from deceleration to acceleration of the Universe for SRDE and ΛCDM occur at the redshift $z_{q=0} \sim 0.4$, comparable with that estimated from 157 gold data ($z_t \simeq 0.46 \pm 0.13$) [65], while $z_{q=0} \sim 0.6$ for RDE.

IV. STRUCTURE FORMATION

It is a crucial test for any model of dark energy to study perturbations in the dark matter/baryon component grow during the matter-dominated era. Considering unified models of dark matter and dark energy, such as Chaplygin gas, may suffer unstability [66–71], although SRDE is not a unified model of dark matter and dark energy, it behaves like dust in matter-dominated era, so it is important to study whether this characteristic would affect the growth rate of dark matter/baryon density perturbation and upset the usual structure formation scenario.

In Fig. 5 we compare the evolution of dark matter/baryon density perturbations in SRDE with that in the ΛCDM model by a generated multifunctional module of Boltzmann code [72, 73], which originally based on CAMB [74]. The parameters is the best-fit values as discussed earlier: $\Omega_{k0} = 0$, $\Omega_{m0} = 0.259$ ($\Omega_h = 0.05$, $\Omega_c = 0.204$), and $\alpha = 0.261$. As shown in Fig. 5 the differences between SRDE and the ΛCDM model are very small, almost invisible for the
large scale perturbations (e.g. \( k = 0.01 \) h Mpc\(^{-1} \) modes); For the small scale perturbations (e.g. \( k = 0.2 \) h Mpc\(^{-1} \) modes), the amplitudes of \( \delta_c \) and \( \delta_b \) in SRDE are slightly larger than these in ΛCDM model, due to the extra dust-like component in SRDE.

The matter power spectra at different redshifts is plotted in Fig. 6. The turnover of matter power spectra occurs at smaller scale compared with the ΛCDM model as showed in Fig. 6, this is because the extra dust-like component appears in SRDE, then in turn it will shift the matter-radiation equality \( a_{eq} \) to small value. From Fig. 6, we also can conclude that the growth rate of SRDE is somewhat different from the ΛCDM due to different ratios of matter power spectrum of SRDE to that of the ΛCDM model at different redshifts. However, we should say that the deviation of the shapes of the spectra from ΛCDM model is small, and it is expected to be fitted well with the observation by adjusting other parameters, such as \( \sigma_8 \) and \( n_S \).

To compare with the CMB anisotropy of ΛCDM model, we present CMB angular power spectra of SRDE in Fig. 7. The plot shows that two results are consistent with each other well on the large scale. On the small scale, the difference is still in acceptable level due to large error bars in this range. On the other hand, this mean we could test SRDE from small scale data, for example, Planck data in the future. These kinds of data could be helpful to distinguish SRDE from ΛCDM model.

V. CONCLUSIONS AND DISCUSSIONS

In this article, we have shown that replace Ricci scalar curvature in RDE model with spatial Ricci scalar curvature, \( \rho_X \propto R_s \), the resulting SRDE model is viable phenomenologically. The dark energy component in SRDE contains a term evolves like nonrelativistic matter, a term increases with decreasing redshift, and a term serves as dark radiation which RDE doesn’t have. Like RDE, SRDE avoided the causality problem of holographic dark energy, because the dark energy is determined by the locally determined spatial Ricci scalar curvature, not the future event horizon. Because SRDE model is not associated Planck or other high energy physics scale, but with the size of space-time curvature, the fine tuning problem can be avoided.

Assuming that the Universe is spatially flat, we have placed observational constraints on SRDE scenario with the Union+CFA3 sample of 397 SNIa and the BAO measurement from the SDSS. For SRDE, we have obtained the best fit values of the parameters at 68% confidence level: \( \Omega_{m0} = 0.259 \pm 0.016 \) and \( \alpha = 0.261 \pm 0.0122 \) with \( \chi^2_{\text{min}} = 470.007 \) (dof= 1.187). With these values of parameters, we have studied evolutions of Hubble parameters, parameters of EoS and the deceleration parameters. SRDE evolves like nonrelativistic matter when \( z \rightarrow 2 \), while RDE not. The present values of the deceleration parameter \( q(z) \) for SRDE is found to be \( q_{z=0} \sim -0.85 \). The phase transition from deceleration to acceleration of the Universe for SRDE occurs at the redshift \( z_q \sim 0.4 \), comparable with that estimated from 157 gold data (\( z_t \simeq 0.46 \pm 0.13 \)) [65]. We found the equation of state of SRDE crosses \(-1\) at \( z \simeq -0.14 \).

We have discussed the dark matter/baryon density perturbations, the differences between SRDE and the ΛCDM
FIG. 6: The matter power spectra at different redshifts. From top to bottom: $z = 0$, $z = 5$, $z = 10$, and $z = 20$. The solid and dashed curves represent SRDE and ΛCDM model, respectively.

FIG. 7: The theoretical CMB temperature angular power spectrum of SRDE (solid curve) compared with ΛCDM model (dashed curve). We normalize two amplitudes of spectra to same at the first peak.
model are very small for the large scale perturbations, while a little larger for the small scale perturbations. As expected, due to the extra dust-like component, the growth rate of SRDE differs from that in ΛCDM model, and the matter-radiation equality occurred at smaller \(a_{eq}\). We also have shown that the CMB angular power spectra of SRDE is consistent with that of ΛCDM on the large scale, while difference slightly on the small scale. This mean we could test SRDE from small scale data.

The properties of SRDE, the presented dark radiation like as in brane dark energy and in Hořava-Lifshitz cosmology and the behavior crossing \(-1\) like as in quintom, may be interesting in future study. We note, however, we have been inspired by the holographic principle when constructing SRDE, SRDE does not necessarily have to be connected with the holographic principle. Although SRDE is phenomenologically successful and theoretically interesting, its physical mechanism is await further study.

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