Observational Constraints on Interacting Model of New Agegraphic Dark Energy and Alleviation of Cosmic Age Problem

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Many dark energy models fail to pass the cosmic age test via the old quasar APM 08279+5255 at redshift $z = 3.91$, even the ΛCDM model and the holographic dark energy model are not exception. In this paper, we focus on the topic of age problem in the new agegraphic dark energy (NADE) model. We determine the age of the universe in the NADE model by using the fitting result of observational data including type Ia supernovae (SNIa), baryon acoustic oscillation (BAO) and cosmic microwave background (CMB). It is shown that the NADE model also faces the challenge of the age problem caused by the old quasar APM 08279+5255. In order to overcome such a difficulty, we consider the possible interaction between dark energy and matter. We show that the old quasar APM 08279+5255 at redshift $z = 3.91$ can be successfully accommodated in the interacting new agegraphic dark energy (INADE) model at 2σ level under the current observational constraints.

PACS numbers: 95.36.+x, 98.80.Es, 98.80.-k

I. INTRODUCTION

At the present stage, our universe is undergoing an accelerated expansion, which has been confirmed by lots of astronomical observations such as type Ia supernovae (SNIa) [1], large scale structure (LSS) [2] and cosmic microwave background (CMB) [3], etc. All these observations indicate the existence of "dark energy" with negative pressure. The most important theoretical candidate of dark energy is the cosmological constant Λ, which can fit the observations well, but is also plagued with some severe theoretical difficulties, such as the so called "fine-tuning" problem and the "cosmic coincidence" problem [4]. During the past decade, in order to unveil the nature of dark energy, theorists also proposed many phenomenological models of dark energy, e.g., quintessence [5], k-essence [6], tachyon [7], phantom [8], quintom [9], braneworld [10], Chaplygin gas [11], etc. Besides, the possibility of that dark energy might interact with dark matter, owing to their unknown nature, has also been seriously considered in many works to help solve the cosmic coincidence problem [12] and the cosmic doomsday problem [13]. For reviews of dark energy, see, e.g., Ref. [14].

In recent years, it was found that many dark energy models get into trouble when tested by some old high redshift objects (OHROs). It is obvious that the universe cannot be younger than its constituents, so the age of some astronomical objects (at some redshift), if measured accurately, can be used to test cosmological models according to this simple age principle. Now, there are some OHROs discovered, for example, the 3.5 Gyr old galaxy LBDS 53W091 at redshift $z = 1.55$ [15] and the 4.0 Gyr old galaxy LBDS 53W069 at redshift $z = 1.43$ [16]. In particular, the old quasar APM 08279 + 5255 at redshift $z = 3.91$ is an important one, which has been used as a "cosmic clock" to constrain cosmological models. Its age is estimated to be $2.0 - 3.0$ Gyr [17]. These three OHROs at $z = 1.43$, 1.55 and 3.91 have been used to test many dark energy models, including the ΛCDM model [18], the general EoS dark energy model [19], the scalar-tensor quintessence model [20], the $f(R) = \sqrt{R^2 - R_0^2}$ model [21], the DGP braneworld model [22], the power-law parameterized quintessence model [23], the Yang-Mills condensate model [24], the holographic dark energy model [25], the agegraphic dark energy model [26] and so on. These investigations show that the two OHROs at $z = 1.43$ and 1.55 can be easily accommodated in most dark energy models, whereas the OHRO at $z = 3.91$ cannot, even in the ΛCDM model [18] and the holographic dark energy model [25]. In this paper, we will investigate the cosmic age problem in the new agegraphic dark energy (NADE) model. We will show that the NADE model also faces the challenge of such an age problem. In order to escape from the cosmic age crisis, we consider the possible interaction between dark energy and dark matter. We will check whether the age problem can be solved successfully in the interacting new agegraphic dark energy (INADE) model. Of course, our discussions are based on the current observational constraints on the models. So, we will first place observational constraints on the NADE and INADE models, and then discuss the cosmic age problem.

II. THE NEW AGEGRAPHIC DARK ENERGY MODEL WITH INTERACTION

In this section, we describe the interacting new agegraphic dark energy in a flat universe. Many theorists believe that we cannot entirely understand the nature of dark energy before a complete theory of quantum gravity is established [27]. In the circumstance that a full theory of quantum gravity is not yet available, it is more realistic to consider the possible cosmological consequences of some fundamental principles of quantum gravity. The holographic principle [28] is commonly believed as a fundamental principle of quantum gravity, so it is expected to play an essential role in investigating dark energy [29]. Along this line, a model of holographic dark energy has been proposed [30] (see also, e.g., Refs. [31, 32]). The agegraphic dark energy model [33] is constructed in light of the Károlyházy relation [34] and corresponding energy fluctuations of space-time. Actually, it has been proven that the agegraphic dark energy scenario is also a kind of holographic model of dark energy [33]. In such a holographic model, the UV problem of dark energy is converted into an IR problem, since the dark energy density is inversely proportional to the square of the IR length scale, $\rho_{de} \sim L^{-2}$. In the old version of agegraphic dark energy model [33], the IR cutoff is chosen as the age of the universe t (here it should be pointed out that the light speed has already been taken to be 1, so time and length have the same dimension). However, there are some inner inconsistencies in this model; for details see Ref. [35]. So, in this paper, we only discuss the new version of the agegraphic dark energy model [35].

In the new agegraphic dark energy model, the IR cutoff is chosen to be the conformal age of the universe,

$$\eta \equiv \int_0^t \frac{d\tilde{t}}{a} = \int_0^a \frac{d\tilde{a}}{H\tilde{a}^2}, \tag{1}$$

so the energy density of NADE reads

$$\rho_q = \frac{3n^2 m_p^2}{\eta^2}, \tag{2}$$

where n is a numerical parameter and m_p is the reduced Planck mass.

If we consider a spatially flat FRW universe containing agegraphic dark energy and pressureless matter, the corresponding Friedmann equation reads

$$H^2 = \frac{1}{3m_p^2}\left(\rho_m + \rho_q\right), \tag{3}$$

or equivalently,

$$E(z) \equiv \frac{H(z)}{H_0} = \left(\frac{\Omega_{m0}(1+z)^3}{1-\Omega_q(z)}\right)^{1/2}, \tag{4}$$

where Ω_{m0} is the present fractional matter density, and $\Omega_q \equiv \rho_q/(3m_p^2 H^2)$. From Eq. (2), it is easy to find that

$$\Omega_q = \frac{n^2}{H^2\eta^2}. \tag{5}$$

Obviously, $\Omega_m \equiv \rho_m/(3m_p^2 H^2) = 1 - \Omega_q$ from Eq. (3). By using Eqs. (1), (2), (3) and (5) and the energy conservation equation $\dot{\rho}_m + 3H\rho_m = 0$, we obtain the equation of motion for Ω_q:

$$\Omega_q' = \Omega_q\left(1-\Omega_q\right)\left(3 - \frac{2}{na}\sqrt{\Omega_q}\right), \tag{6}$$

where the prime denotes the derivative with respect to $x \equiv \ln a$. Since $\frac{d}{dx} = -(1+z)\frac{d}{dz}$, we get

$$\frac{d\Omega_q}{dz} = -\frac{\Omega_q}{1+z}\left(1-\Omega_q\right)\left(3 - \frac{2(1+z)}{n}\sqrt{\Omega_q}\right). \tag{7}$$

From the energy conservation equation $\dot{\rho}_q + 3H(\rho_q + p_q) = 0$, as well as Eqs. (2) and (5), it is easy to find that the equation-of-state (EoS) parameter of the NADE is given by

$$w_q = -1 + \frac{2}{3na}\sqrt{\Omega_q}. \tag{8}$$

The NADE model has been studied extensively; see, e.g., Refs. [36, 37]. In the following, we shall extend the NADE model by considering the interaction between dark energy and matter.

Assuming that dark energy and matter exchange energy through the interaction term Q, the continuity equations become

$$\dot{\rho}_q + 3H\left(\rho_q + p_q\right) = -Q, \tag{9}$$

$$\dot{\rho}_m + 3H\rho_m = Q. \tag{10}$$

Owing to the lack of the knowledge of micro-origin of the interaction, we simply follow other work on the interacting dark energy and parameterize the interaction term generally as $Q = 3H(\alpha\rho_q + \beta\rho_m)$, where α and β are the dimensionless coupling constants. For reducing the complication and the number of parameters, one often considers the following three cases: (i) $\alpha = b$ and $\beta = 0$, denoted as INADE1, (ii) $\alpha = 0$ and $\beta = b$, denoted as INADE2, (iii) $\alpha = \beta = b$, denoted as INADE3. Note that according to our convention $b > 0$ means that dark energy decays to matter, while $b < 0$ means that matter decays into dark energy. In the cases (i) and (iii), negative b would lead to unphysical consequence that ρ_m becomes negative in the far future. For negative b in the case (ii), no such difficulty exists. In Ref. [38], from the thermodynamical view, it is argued that the second law of thermodynamics strongly favors that dark energy decays into matter. So, in general, b is taken to be positive.

However, recently, it is found that the observations may favor the decaying of matter into dark energy [39, 40]. In particular, in Ref. [41], in a way independent of specific interacting forms, the authors fitted the interaction term Q with observations. They found that Q is likely to cross the non-interacting line ($Q = 0$), namely, the sign of interaction Q changed, around $z = 0.5$. This raises a remarkable challenge to the interacting models, since the general phenomenological forms of interaction, as shown in the above, cannot give the possibility of changing signs. As noted in Ref. [41], more general forms of interaction should be considered. For this reason, a new form of interaction, (iv) $\alpha = -\beta = b$, denoted as INADE4, was considered in Ref. [42]. Obviously, for this case, in the early stage, since $\rho_m > \rho_q$, Q is negative. However, Q may change sign from negative to positive when the expansion of the universe changes from deceleration to acceleration. The parameter b in this case is also assumed to be positive, since negative b would lead to a negative ρ_m in the far future.

For clearness, we denote the interaction term Q aforementioned as

$$Q = \begin{cases} 3bH\rho_q, \\ 3bH\rho_m, \\ 3bH(\rho_q + \rho_m), \\ 3bH(\rho_q - \rho_m). \end{cases} \tag{11}$$

Note that in the cases (i), (iii) and (iv) the parameter b is always assumed to be positive in the literature. However, in the present work, instead of making such an assumption on b, we let b be totally free and let the observational data tell us the true story, no matter whether the ultimate fate of the universe is ridiculous or not.

Differentiating Eq. (5) with respect to $\ln a$ and using Eq. (1), we get

$$\Omega_q' = \Omega_q \left(-2\frac{\dot{H}}{H^2} - \frac{2}{na}\sqrt{\Omega_q} \right). \tag{12}$$

Differentiating Eq. (3) with respect to time t and combining Eqs. (1), (5), (9) and (10), we can easily find that

$$-\frac{\dot{H}}{H^2} = \frac{3}{2}\left(1 - \Omega_q\right) + \frac{\Omega_q^{3/2}}{na} - \frac{Q}{6m_p^2 H^3}. \tag{13}$$

Therefore, we obtain the equation of motion for Ω_q,

$$\Omega_q' = \Omega_q \left[\left(1 - \Omega_q\right)\left(3 - \frac{2}{na}\sqrt{\Omega_q}\right) - Q_1 \right], \tag{14}$$

or equivalently,

$$\frac{d\Omega_q}{dz} = -\frac{\Omega_q}{1+z}\left[\left(1 - \Omega_q\right)\left(3 - \frac{2\,(1+z)}{n}\sqrt{\Omega_q}\right) - Q_1 \right], \tag{15}$$

where

$$Q_1 \equiv \frac{Q}{3m_p^2 H^3}. \tag{16}$$

From Eqs. (5) and (9), we get the EoS parameter of dark energy:

$$w_q = -1 + \frac{2}{3na}\sqrt{\Omega_q} - Q_2, \tag{17}$$

where

$$Q_2 \equiv \frac{Q}{3H\rho_q}. \tag{18}$$

It is convenient to define the effective EoS parameters for dark energy and matter as

$$w_q^{(e)} = w_q + \frac{Q}{3H\rho_q}, \tag{19}$$

$$w_m^{(e)} = -\frac{Q}{3H\rho_m}. \tag{20}$$

According to the definition of the effective EoS parameters, the continuity equations for dark energy and matter can be re-expressed in forms of energy conservation:

$$\dot{\rho}_q + 3H(1 + w_q^{(e)})\rho_q = 0, \tag{21}$$

$$\dot{\rho}_m + 3H(1 + w_m^{(e)})\rho_m = 0. \tag{22}$$

Taking the aforementioned four cases of interaction, one can obtain

$$w_m^{(e)} = \begin{cases} -b\frac{\Omega_q}{1-\Omega_q} & Q = 3bH\rho_q, \\ -b & Q = 3bH\rho_m, \\ -b\left(1 + \frac{\Omega_q}{1-\Omega_q}\right) & Q = 3bH(\rho_q + \rho_m), \\ -b\left(-1 + \frac{\Omega_q}{1-\Omega_q}\right) & Q = 3bH(\rho_q - \rho_m). \end{cases} \tag{23}$$

Now, the Friedmann equation can be expressed as

$$H(z) = H_0 E(z), \tag{24}$$

where

$$E(z) = \left[\frac{(1 - \Omega_{q0})e^{3\int_0^z (1+w_m^{(e)})d\tilde{z}}}{1 - \Omega_q(z)}\right]^{1/2}. \tag{25}$$

In the above equation, $\Omega_q(z)$ can be obtained by numerically solving Eq. (15) with initial condition $\Omega_q(z_{ini}) = n^2(1 + z_{ini})^{-2}/4$ at $z_{ini} = 2000$ [36]. While this initial condition is obtained from NADE model without interaction in the matter-dominated epoch, it is still suitable to an interacting model of new agegraphic dark energy because the contribution of dark energy to the cosmological evolution is negligible in the matter-dominated epoch so that the impact of dark energy on matter can be totally ignored at that times; for details see Ref. [43].

III. OBSERVATIONAL CONSTRAINTS

In this section, we place observational constraints on the NADE and INADE models. For the data, we will use the combination of SNIa, CMB and BAO.

First, we consider the data points of the 557 Union2 SNIa compiled in Ref. [44]. The theoretical distance modulus is defined as

$$\mu_{th}(z_i) \equiv 5\log_{10} D_L(z_i) + \mu_0, \tag{26}$$

where $\mu_0 \equiv 42.38 - 5\log_{10} h$ with h the Hubble constant H_0 in units of 100 km/s/Mpc, and the Hubble-free luminosity distance

$$D_L(z) = (1+z)\int_0^z \frac{d\tilde{z}}{E(\tilde{z};\mathbf{p})}, \tag{27}$$

where $E \equiv H/H_0$, and $\mathbf{p}$ denotes the model parameters. Correspondingly, the χ^2 for the 557 Union2 SNIa data is given by

$$\chi^2_\mu(\mathbf{p}) = \sum_{i=1}^{557} \frac{[\mu_{obs}(z_i) - \mu_{th}(z_i)]^2}{\sigma^2(z_i)}, \tag{28}$$

where σ is the corresponding 1σ error of distance modulus for each supernova. The parameter μ_0 is a nuisance parameter but it is independent of the data points. Following Ref. [45], the minimization with respect to μ_0 can be made trivially by expanding the χ^2 of Eq. (28) with respect to μ_0 as

$$\chi^2_\mu(\mathbf{p}) = A - 2\mu_0 B + \mu_0^2 C, \tag{29}$$

where

$$A(\mathbf{p}) = \sum_{i=1}^{557} \frac{[\mu_{obs}(z_i) - \mu_{th}(z_i;\mu_0 = 0,\mathbf{p})]^2}{\sigma^2_{\mu_{obs}}(z_i)},$$

$$B(\mathbf{p}) = \sum_{i=1}^{557} \frac{\mu_{obs}(z_i) - \mu_{th}(z_i;\mu_0 = 0,\mathbf{p})}{\sigma^2_{\mu_{obs}}(z_i)},$$

$$C = \sum_{i=1}^{557} \frac{1}{\sigma^2_{\mu_{obs}}(z_i)}.$$

Evidently, Eq. (29) has a minimum for $\mu_0 = B/C$ at

$$\tilde{\chi}^2_\mu(\mathbf{p}) = A(\mathbf{p}) - \frac{B(\mathbf{p})^2}{C}. \tag{30}$$

Since $\chi^2_{\mu,min} = \tilde{\chi}^2_{\mu,min}$, instead minimizing χ^2_μ we will minimize $\tilde{\chi}^2_\mu$ which is independent of the nuisance parameter μ_0. Obviously the best-fit value of h can be given by the corresponding $\mu_0 = B/C$ at the best fit.

Next, we consider the cosmological observational data from WMAP and SDSS. For the WMAP data, we use the CMB shift parameter R; for the SDSS data, we use the parameter A of the BAO measurement. It is widely believed that both R and A are nearly model-independent and contain essential information of the full WMAP CMB and SDSS BAO data [46].

The shift parameter R is given by [46, 47]

$$R \equiv \Omega_{m0}^{1/2} \int_0^{z_*} \frac{d\tilde{z}}{E(\tilde{z})}, \tag{31}$$

where the redshift of recombination $z_* = 1091.3$ which has been updated in the WMAP 7-year data [48]. The shift parameter R relates the angular diameter distance to the last scattering surface, the comoving size of the sound horizon at z_* and the angular scale of the first acoustic peak in CMB power spectrum of temperature fluctuations [46, 47]. The value of R has been updated to 1.725 ± 0.018 from the WMAP 7-year data [48]. On the other hand, the distance parameter A of the measurement of the BAO peak in the distribution of SDSS luminous red galaxies [49] is given by

$$A \equiv \Omega_{m0}^{1/2} E(z_b)^{-1/3} \left[\frac{1}{z_b} \int_0^{z_b} \frac{d\tilde{z}}{E(\tilde{z})} \right]^{2/3}, \tag{32}$$

where $z_b = 0.35$. In Ref. [50], the value of A has been determined to be $0.469\,(n_s/0.98)^{-0.35} \pm 0.017$. Here the scalar spectral index n_s is taken to be 0.963, which has been updated from the WMAP 7-year data [48]. So the total χ^2 is given by

$$\chi^2 = \tilde{\chi}_\mu^2 + \chi_{CMB}^2 + \chi_{BAO}^2, \tag{33}$$

where $\tilde{\chi}_\mu^2$ is given in Eq. (30), $\chi_{CMB}^2 = (R - R_{obs})^2/\sigma_R^2$ and $\chi_{BAO}^2 = (A - A_{obs})^2/\sigma_A^2$. The best-fit model parameters are determined by minimizing the total χ^2. The 68.3% confidence level is determined by $\Delta\chi^2 \equiv \chi^2 - \chi_{min}^2 \leq 1.0$, 2.3 and 3.53 for $n_p = 1$, 2 and 3, respectively, where n_p is the number of free model parameters. Similarly, the 95.4% confidence level is determined by $\Delta\chi^2 \equiv \chi^2 - \chi_{min}^2 \leq 4.0$, 6.17 and 8.02 for $n_p = 1$, 2 and 3, respectively.

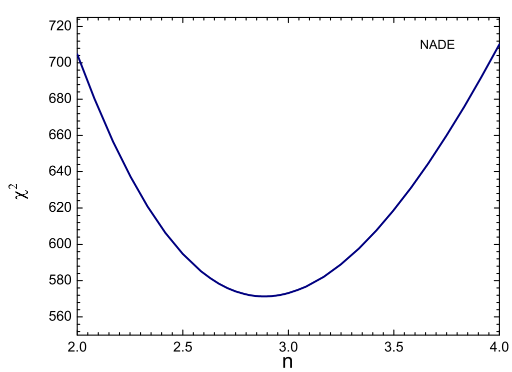

FIG. 1: The plot of χ^2 versus n for the NADE model.

TABLE I: The fit values for the NADE and HDE models. Note that here the NADE model is regarded as a two-parameter model.

Model	Ω_{m0}	n/c	χ^2_{min}
NADE	$0.270^{+0.021}_{-0.020}\,(1\sigma)^{+0.036}_{-0.033}\,(2\sigma)$	$206.762^{+131.212}_{-69.060}\,(1\sigma)^{+131.212}_{-71.610}\,(2\sigma)$	542.915
HDE	$0.276^{+0.022}_{-0.020}\,(1\sigma)^{+0.036}_{-0.033}\,(2\sigma)$	$0.748^{+0.095}_{-0.085}\,(1\sigma)^{+0.164}_{-0.134}\,(2\sigma)$	543.056

Now, let us discuss the observational constraints on the NADE model. The NADE model is a one-parameter model, and the sole model parameter is n. Solving Eq. (7) numerically with the initial condition $\Omega_q(z_{ini}) = n^2(1+z_{ini})^{-2}/4$ at $z_{ini} = 2000$ and substituting the resultant $\Omega_q(z)$ into Eq. (4), the corresponding $E(z)$ can be obtained.

For the NADE model, the cosmological constraints are obtained: $n = 2.886^{+0.084}_{-0.082}$ at 1σ level and $n = 2.886^{+0.169}_{-0.163}$ at 2σ level. At the best fit we have $\chi^2_{min} = 571.338$, $h = 0.685$ and $\Omega_{m0} = 0.265$. In Fig. 1, we plot the relation of $\chi^2 - n$ for the NADE model.

According to Ref. [35], the NADE model is always considered as a one-parameter model, and the initial condition is chosen to be $\Omega_q(z_{ini}) = n^2(1+z_{ini})^{-2}/4$ at $z_{ini} = 2000$. However, we can also adopt another perspective that regards the NADE model as a two-parameter model. If so, we are interested in what result the observational data will tell us. To see this, we choose the initial condition $\Omega_{q0} = 1 - \Omega_{m0}$ for the NADE model, and then the model becomes a two-parameter model with the free parameters Ω_{m0} and n. In Fig. 2 (*Left*), we plot the contours of 68.3% and 95.4% confidence levels in the $\Omega_{m0} - n$ plane for the NADE model. The fit values for the model parameters are also shown in Table I.

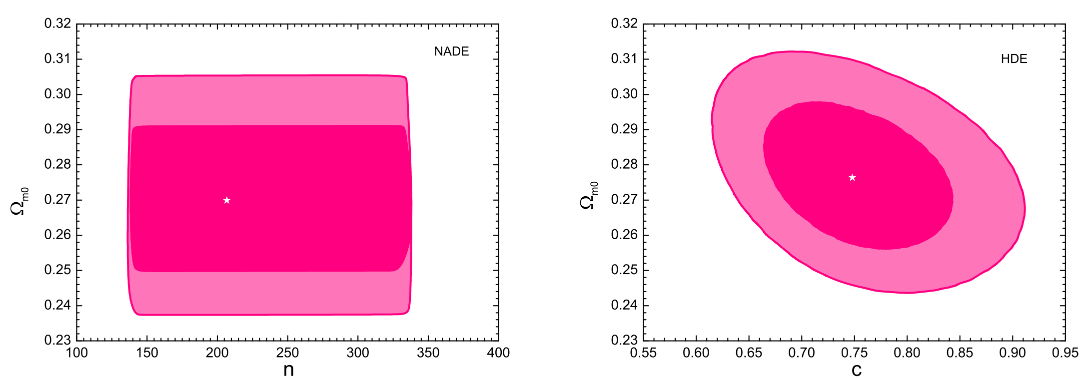

FIG. 2: The probability contours at 1σ and 2σ confidence levels in the $\Omega_{m0} - n$ plane for the NADE model (*Left*) and in the $\Omega_{m0} - c$ plane for the HDE model (*Right*). Note that here the NADE model is regarded as a two-parameter model. The star denotes the best fit.

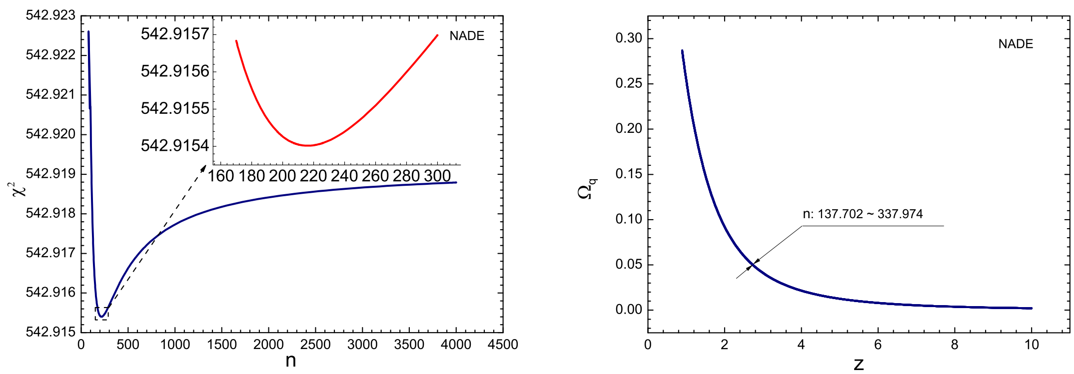

FIG. 3: (*Left*) The plot of χ^2 versus n for the two-parameter NADE model with $\Omega_{m0} = 0.270$. (*Right*) The plot of Ω_q versus z for the two-parameter NADE model with n varying from 137.702 to 337.974.

Now that the NADE model is viewed as a two-parameter model, it is of great interest to make a direct comparison with the holographic dark energy (HDE) model. The equation of motion for the HDE fractional density Ω_Λ is given by [30]

$$\Omega'_\Lambda = \Omega_\Lambda (1 - \Omega_\Lambda)\left(1 + \frac{2}{c}\sqrt{\Omega_\Lambda}\right), \tag{34}$$

where c is a numerical parameter just as n in the NADE model. Using $\frac{d}{dx} = -(1+z)\frac{d}{dz}$, we get

$$\frac{d\Omega_\Lambda}{dz} = -\frac{\Omega_\Lambda}{1+z}(1 - \Omega_\Lambda)\left(1 + \frac{2}{c}\sqrt{\Omega_\Lambda}\right). \tag{35}$$

In Fig. 2 (*Right*), we plot the contours of 1σ and 2σ confidence levels in the $\Omega_{m0} - c$ plane for the HDE model. The fit values for the model parameters are also presented in Table I.

Comparing with the HDE model, we find that the NADE model can give a lower χ^2_{min}. Notwithstanding, it is obviously seen from Fig. 3 (*Left*) that the data are not able to effectively constrain the parameter n, i.e., a very large range of values of n are allowed by the data. Fig. 3 (*Left*) shows the plot of χ^2 versus n, with fixed Ω_{m0} (it is fixed to be the best-fit value, 0.270). It is noticed that χ^2 tends to be a constant as n becomes large and the value of the constant χ^2 is just slightly larger than χ^2_{min}, so it is not surprising that n can get values from 137.702 to 337.974 at 1σ level. Now, let us discuss the cosmological consequence of such a strong degeneracy of n. For this purpose, we plot the evolution of $\Omega_q(z)$ with n varying from 137.702 (the lower limit value at 1σ) to 337.974 (the upper limit value at 1σ) in Fig. 3 (*Right*). We see that the curves with different n almost totally degenerate in a narrow region. This indicates that the cosmological evolution tends to be the same when n takes large values in this model. In fact, we can also infer this from Eq. (7). We notice that the term $\frac{2(1+z)}{n}\sqrt{\Omega_q}$ is negligible as n is large enough. Thus, Eq. (7) reduces to

$$\frac{d\Omega_q}{dz} = -\frac{3\Omega_q}{1+z}\left(1 - \Omega_q\right). \tag{36}$$

TABLE II: The fit values for the NADE and INADE models.

Model	n	b	χ^2_{min}
NADE	$2.886^{+0.084}_{-0.082}\,(1\sigma)^{+0.169}_{-0.163}\,(2\sigma)$	N/A	571.338
INADE1	$3.199^{+0.194}_{-0.181}\,(1\sigma)^{+0.324}_{-0.290}\,(2\sigma)$	$0.029^{+0.008}_{-0.009}\,(1\sigma)^{+0.014}_{-0.015}\,(2\sigma)$	552.674
INADE2	$3.245^{+0.218}_{-0.202}\,(1\sigma)^{+0.364}_{-0.322}\,(2\sigma)$	$0.016^{+0.006}_{-0.006}\,(1\sigma)^{+0.010}_{-0.010}\,(2\sigma)$	556.492
INADE3	$3.236^{+0.207}_{-0.193}\,(1\sigma)^{+0.344}_{-0.307}\,(2\sigma)$	$0.010^{+0.003}_{-0.004}\,(1\sigma)^{+0.006}_{-0.006}\,(2\sigma)$	555.015
INADE4	$3.208^{+0.239}_{-0.214}\,(1\sigma)^{+0.406}_{-0.339}\,(2\sigma)$	$-0.027^{+0.013}_{-0.015}\,(1\sigma)^{+0.022}_{-0.025}\,(2\sigma)$	561.634

Solving this equation we obtain ρ_q = constant. Therefore, from the above analysis, we find that when the NADE model is regarded as a two-parameter model, the dark energy is more likely to behave as a cosmological constant. So, in the rest of this paper, we confine our discussions to the single-parameter NADE model.

Next, we discuss the cases of the INADE model. Different cases of the INADE model are denoted as INADE1, INADE2, INADE3 and INADE4, respectively. Table II summarizes the fit results for the four cases of the INADE model. For comparison, we also list the results of the NADE model. In this table we show the best-fit, 1σ and 2σ values of the parameters and the χ^2_{min} values of the models. At the best fit, we have $h = 0.692, 0.690, 0.691$ and 0.688 and $\Omega_{m0} = 0.240, 0.236, 0.237$ and 0.239 for the four interacting cases. One can see from Table II that the INADE1, INADE2 and INADE3 models have a similar χ^2_{min}, and the INADE4 model gives a larger χ^2_{min} than the above three cases, but all lower than the NADE model. Besides, a distinctive feature in the INADE4 model is that the fit values of parameter b are all negative in 2σ range. As discussed in the previous section, a negative b would lead to a negative ρ_m in the future. So, in this sense, we have shown that the INADE4 is not a reasonable model according to the observational data analysis. For the 1σ and 2σ contours in the $n-b$ plane for the four INADE models, we refer the reader to Fig. 5 whereby we discuss the high-z cosmic age problem caused by the old quasar APM 08279+5255 at redshift $z = 3.91$.

IV. AGE PROBLEM: CHALLENGE AND WAY OUT

The age of the universe at redshift z is given by

$$t(z) = \int_z^\infty \frac{dz'}{(1+z')H(z')}. \tag{37}$$

It is convenient to introduce a dimensionless cosmic age

$$T_{cos}(z) \equiv H_0 t(z) = \int_z^\infty \frac{dz'}{(1+z')E(z')}, \tag{38}$$

where $E(z) \equiv H(z)/H_0$. At any redshift, the age of the universe should not be smaller than the age of any object in the universe, namely, $T_{cos}(z) \geq T_{obj}(z) \equiv H_0 t_{obj}(z)$, where $t_{obj}(z)$ is the age of the OHRO at redshift z. For convenience, we define a dimensionless quantity, the ratio of the cosmic age and the OHRO age,

$$\tau(z) \equiv \frac{T_{cos}(z)}{T_{obj}(z)} = H_0^{-1} t_{obj}^{-1}(z) \int_z^\infty \frac{dz'}{(1+z')E(z')}. \tag{39}$$

Thus, the condition $\tau(z) \geq 1$ is equivalent to $T_{cos}(z) \geq T_{obj}(z)$.

First, we will test the NADE model with the ages of the OHROs. We will use three OHROs: the old galaxy LBDS 53W091 at redshift $z = 1.55$, the old galaxy LBDS 53W069 at $z = 1.43$ and the old quasar APM 08279+5255 at $z = 3.91$. The ages of the two OHROs at $z = 1.55$ and $z = 1.43$ are 3.5 Gyr and 4.0 Gyr, respectively. For the age of the OHRO at $z = 3.91$, following Ref. [25], we use the lower bound estimated, $t_{obj}(3.91) = 2.0$ Gyr. We calculate the age of the universe at different redshifts using the best-fit results of the NADE model, $n = 2.886$ and $h = 0.685$, and then we obtain the values of τ: $\tau(1.55) = 1.215$, $\tau(1.43) = 1.136$, and $\tau(3.91) = 0.833$, also shown in Table III. So, the NADE model can easily accommodate the former two OHROs at $z = 1.55$ and 1.43, respectively, but cannot accommodate the old quasar at $z = 3.91$. Of course, the above result is only for the best fit. Now, let us see whether the old quasar can be accommodated within the 2σ range. We show the result in Fig. 4. In this figure, the blue line represents $\tau(3.91)$ with n running over the 2σ range; for reducing the complication, we fix h at the best fit in the calculation. It is clear to see that the NADE model indeed cannot accommodate the old quasar APM 08279+5255, and the age problem raises a serious challenge to the NADE model.

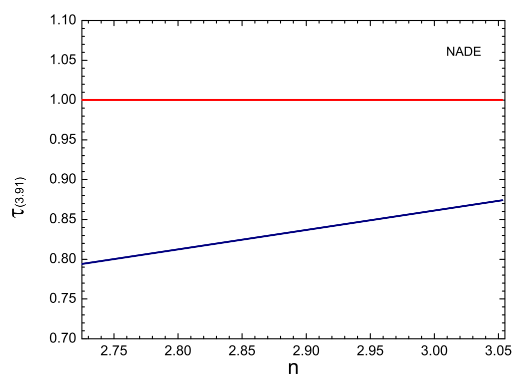

FIG. 4: The plot of $\tau(3.91)$ versus n for the NADE model. The region avoiding the age problem is that above the $\tau(3.91) = 1$ line (red).

TABLE III: The values of $\tau(z)$ in the NADE, INADE1, INADE2, INADE3 and INADE4 models at best fit concerning LBDS 53W091 at $z = 1.55$, LBDS 53W069 at $z = 1.43$, and the old quasar APM 08279+5255 at $z = 3.91$.

Model $(n,\ b,\ h)$	$\tau(1.55)$	$\tau(1.43)$	$\tau(3.91)$
NADE (2.886, 0, 0.685)	1.215	1.136	0.833
INADE1 (3.199, 0.029, 0.692)	1.326	1.238	0.919
INADE2 (3.245, 0.016, 0.690)	1.318	1.230	0.923
INADE3 (3.236, 0.010, 0.691)	1.323	1.235	0.923
INADE4 (3.208, −0.027, 0.688)	1.290	1.204	0.908

To overcome this difficulty, we seek help from the possible interaction between dark energy and matter. Thus, next, we explore whether the old quasar APM 08279+5255 can be accommodated in the INADE model. Based on the above results of observational constraints, we can easily accomplish this task. Using the best-fit values, we obtain the values of $\tau(z)$ for the four INADE models, listed in Table. III. We can see that the $\tau(z)$ values indeed increase when the interaction is involved in the model. Notwithstanding, for the old quasar at $z = 3.91$, the values of $\tau(3.91)$ only increase from 0.83 to about 0.92, not yet exceed 1. So, if only with the best fit, the INADE models still cannot solve the age crisis. Of course, it is evident that the age problem has been greatly alleviated via the interaction between dark energy and matter. As the next step, we will scan the whole parameter space to explore whether there exists area being able to realize $\tau(3.91) > 1$. We show the result in Fig. 5. The red line contains all points with $\tau(3.91) = 1$, where the best-fit h used, and thus the right region of which denotes $\tau(3.91) > 1$, as indicated by the arrows. From this figure, we can clearly see that the red line passes through the 2σ region of the $n - b$ parameter space of the INADE model, for the former three cases. For the fourth case, INADE4, the red line only intersect the edge of the 2σ region. This result again shows that the form of interaction $Q = 3bH(\rho_q - \rho_m)$ is not reasonable, in that it not only has a negative b, but also fails to provide a solution to the high-z cosmic age problem.

The above analysis indicates that the old quasar APM 08279+5255 can be successfully accommodated by the INADE model (at least for the former three cases) at 2σ level. There indeed exists an area within 2σ scope realizing $\tau(3.91) > 1$ and thus successfully solving the age crisis in the NADE model. To be modest, we do not assert that the cosmic age crisis has been totally solved in the INADE model, after all only a small area but not all region of the 2σ scope resides in the right of the $\tau(3.91) = 1$ red line. Though, it should be admitted that the age problem has been significantly alleviated in the INADE model under the current observational constraints.

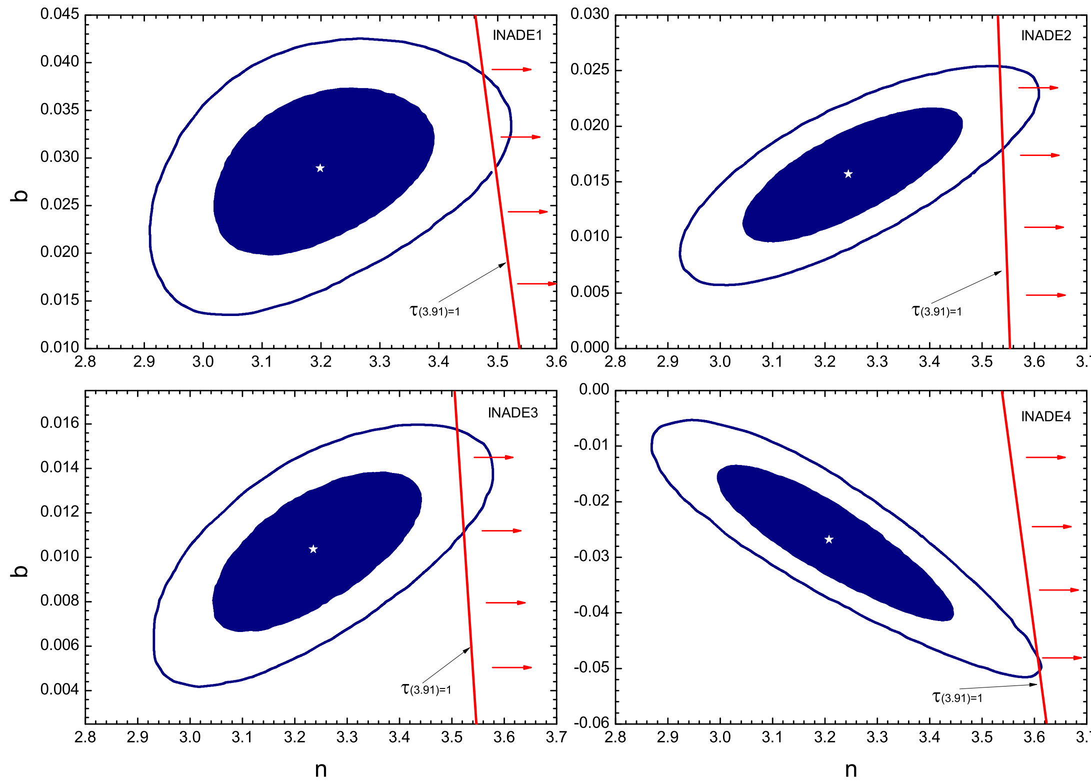

FIG. 5: The probability contours at 1σ and 2σ confidence levels in the $b-n$ plane for the four INADE models. The red line is an isoline with $\tau(3.91) = 1$. The allowed region avoiding the age problem is in the right of the red line, as indicated by the arrows.

V. CONCLUSION

The agegraphic dark energy model originates from the holographic principle of quantum gravity, so it deserves a further investigation. In this paper, we discuss the age problem in the NADE model.

There are lots of work addressing the age problem caused by the old quasar APM 08279+5255 at redshift $z = 3.91$, because this quasar has led many dark energy models to get into trouble, even the ΛCDM model and the holographic dark energy model are not exception. We found in this paper that the NADE model is also afflicted by the age problem. So, we explore whether the involvement of the interaction between dark energy and matter in this model can make the age problem solved.

First, we used the current observational data to constrain the NADE and INADE models. For the data, we use the SNIa Union2 sample, the CMB shift parameter R from 7-yr WMAP, and the BAO parameter A from the SDSS. We determined the age of the universe in the NADE model by using the fitting results and found that the NADE model cannot realize $\tau(3.91) > 1$ within the whole parameter space. By the way, we also explored the cosmological consequence of regarding the NADE model as a two-parameter model. The fitting results show that in such a model the dark energy is more likely to behave as a cosmological constant.

For the possible interaction between dark energy and matter, we considered four phenomenological cases: $Q = 3bH\rho_q$, $Q = 3bH\rho_m$, $Q = 3bH(\rho_q + \rho_m)$ and $Q = 3bH(\rho_q - \rho_m)$. The observational data favor a positive b for the former three cases, but give a negative b for the fourth case. We found that when the interaction is taken into account, the age problem caused by the quasar can be successfully solved in the former three cases of INADE model, at 2σ level. The isoline $\tau(3.91) = 1$ passes through the 2σ region of the $n - b$ parameter space of the INADE model. So, there indeed exists an area within 2σ scope realizing $\tau(3.91) > 1$ and thus successfully solving the age crisis in the NADE model. Though we cannot assert that the age crisis has been removed in the INADE model, since the most part of the parameter space is still in the trouble and only the lower bound age of the quasar is used in the test, we are sure that the age problem has been significantly alleviated in the INADE model under the current observational constraints. So, our work can be viewed as a further support to the INADE model.

Acknowledgments

We would like to thank Xiao-Dong Li for useful discussion and kind help. This work was supported by the Natural Science Foundation of China under Grant Nos. 10705041 and 10975032, as well as the National Ministry of Education of China under the innovation program for undergraduate students.

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[1] A. G. Riess *et al.* [Supernova Search Team Collaboration], Astron. J. **116**, 1009 (1998) [astro-ph/9805201];
S. Perlmutter *et al.* [Supernova Cosmology Project Collaboration], Astrophys. J. **517**, 565 (1999) [astro-ph/9812133].

[2] M. Tegmark *et al.* [SDSS Collaboration], Phys. Rev. D **69**, 103501 (2004) [astro-ph/0310723];
K. Abazajian *et al.* [SDSS Collaboration], Astron. J. **128**, 502 (2004) [astro-ph/0403325];
K. Abazajian *et al.* [SDSS Collaboration], Astron. J. **129**, 1755 (2005) [astro-ph/0410239].

[3] D. N. Spergel *et al.* [WMAP Collaboration], Astrophys. J. Suppl. **148** 175 (2003) [astro-ph/0302209].

[4] S. Weinberg, Rev. Mod. Phys. **61** (1989) 1;
S. M. Carroll, Living Rev. Rel. **4** (2001) 1 [arXiv:astro-ph/0004075].

[5] P. J. E. Peebles and B. Ratra, Astrophys. J. **325** L17 (1988);
B. Ratra and P. J. E. Peebles, Phys. Rev. D **37** 3406 (1988);
C. Wetterich, Nucl. Phys. B **302** 668 (1988);
I. Zlatev, L. M. Wang and P. J. Steinhardt, Phys. Rev. Lett. **82**, 896 (1999) [astro-ph/9807002];

X. Zhang, Phys. Lett. B **648**, 1 (2007) [arXiv:astro-ph/0604484].

[6] C. Armendariz-Picon, V. F. Mukhanov and P. J. Steinhardt, Phys. Rev. Lett. **85**, 4438 (2000) [astro-ph/0004134]; C. Armendariz-Picon, V. F. Mukhanov and P. J. Steinhardt, Phys. Rev. D **63**, 103510 (2001) [astro-ph/0006373].

[7] A. Sen, JHEP **0207**, 065 (2002) [hep-th/0203265]; T. Padmanabhan, Phys. Rev. D **66**, 021301 (2002) [hep-th/0204150]; J. Zhang, X. Zhang and H. Liu, Phys. Lett. B **651**, 84 (2007) [arXiv:0706.1185 [astro-ph]].

[8] R. R. Caldwell, M. Kamionkowski and N. N. Weinberg, Phys. Rev. Lett. **91**, 071301 (2003) [astro-ph/0302506]; Z. K. Guo, Y. S. Piao and Y. Z. Zhang, Phys. Lett. B **594**, 247 (2004) [arXiv:astro-ph/0404225]; X. Zhang, Eur. Phys. J. C **60**, 661 (2009) [arXiv:0708.1408 [gr-qc]].

[9] B. Feng, X. L. Wang and X. M. Zhang, Phys. Lett. B **607**, 35 (2005) [astro-ph/0404224]; Z. K. Guo, Y. S. Piao, X. M. Zhang and Y. Z. Zhang, Phys. Lett. B **608**, 177 (2005) [astro-ph/0410654]; X. Zhang, Commun. Theor. Phys. **44**, 762 (2005); Y. F. Cai, E. N. Saridakis, M. R. Setare and J. Q. Xia, Phys. Rept. **493**, 1 (2010) [arXiv:0909.2776 [hep-th]].

[10] C. Deffayet, G. R. Dvali and G. Gabadadze, Phys. Rev. D **65**, 044023 (2002) [astro-ph/0105068]; V. Sahni and Y. Shtanov, JCAP **0311**, 014 (2003) [astro-ph/0202346]; W. L. Guo and X. Zhang, Phys. Rev. D **79**, 115023 (2009) [arXiv:0904.2451 [hep-ph]]; C. J. Feng and X. Zhang, Phys. Lett. B **680**, 399 (2009) [arXiv:0904.0045 [gr-qc]].

[11] A. Y. Kamenshchik, U. Moschella and V. Pasquier, Phys. Lett. B **511**, 265 (2001) [gr-qc/0103004]; M. C. Bento, O. Bertolami and A. A. Sen, Phys. Rev. D **66**, 043507 (2002) [gr-qc/0202064]; X. Zhang, F. Q. Wu and J. Zhang, JCAP **0601**, 003 (2006) [astro-ph/0411221].

[12] L. Amendola, Phys. Rev. D **62**, 043511 (2000) [arXiv:astro-ph/9908023]; D. Comelli, M. Pietroni and A. Riotto, Phys. Lett. B **571**, 115 (2003) [arXiv:hep-ph/0302080]; X. Zhang, Mod. Phys. Lett. A **20**, 2575 (2005) [arXiv:astro-ph/0503072]; X. Zhang, Phys. Lett. B **611**, 1 (2005) [arXiv:astro-ph/0503075]; R. G. Cai and A. Wang, JCAP **0503**, 002 (2005) [arXiv:hep-th/0411025]; J. Zhang, H. Liu and X. Zhang, Phys. Lett. B **659**, 26 (2008) [arXiv:0705.4145 [astro-ph]]; J. H. He, B. Wang and P. Zhang, Phys. Rev. D **80**, 063530 (2009) [arXiv:0906.0677 [gr-qc]].

[13] M. Li, C. Lin and Y. Wang, JCAP **0805**, 023 (2008) [arXiv:0801.1407 [astro-ph]]; M. Li, X. D. Li, S. Wang, Y. Wang and X. Zhang, JCAP **0912**, 014 (2009) [arXiv:0910.3855 [astro-ph.CO]].

[14] V. Sahni and A. A. Starobinsky, Int. J. Mod. Phys. D **9**, 373 (2000) [arXiv:astro-ph/9904398]; P. J. E. Peebles and B. Ratra, Rev. Mod. Phys. **75**, 559 (2003) [arXiv:astro-ph/0207347]; V. Sahni, Lect. Notes Phys. **653**, 141 (2004) [arXiv:astro-ph/0403324]; E. J. Copeland, M. Sami and S. Tsujikawa, Int. J. Mod. Phys. D **15**, 1753 (2006) [arXiv:hep-th/0603057]; J. Frieman, M. Turner and D. Huterer, Ann. Rev. Astron. Astrophys. **46**, 385 (2008) [arXiv:0803.0982 [astro-ph]].

[15] J. Dunlop, J. Peacock, H. Spinrad, A. Dey, R. Jimenez, D. Stern and R. Windhorst, Nature **381**, 581 (1996); H. Spinrad, A. Dey, D. Stern, J. Dunlop, J. Peacock, R. Jimenez and R. Windhorst, Astrophys. J. **484**, 581 (1997)

[arXiv:astro-ph/9702233].

[16] J. Dunlop, arXiv:astro-ph/9801114.

[17] G. Hasinger, N. Schartel and S. Komossa, Astrophys. J. **573**, L77 (2002) [arXiv:astro-ph/0207005];
S. Komossa and G. Hasinger, arXiv:astro-ph/0207321.

[18] J. S. Alcaniz and J. A. S. Lima, Astrophys. J. **521**, L87 (1999) [arXiv:astro-ph/9902298];
A. Friaca, J. Alcaniz and J. A. S. Lima, Mon. Not. Roy. Astron. Soc. **362**, 1295 (2005) [arXiv:astro-ph/0504031];
J. S. Alcaniz, J. A. S. Lima and J. V. Cunha, Mon. Not. Roy. Astron. Soc. **340**, L39 (2003) [arXiv:astro-ph/0301226];
R. J. Yang and S. N. Zhang, Mon. Not. Roy. Astron. Soc. **407**, 1835 (2010) [arXiv:0905.2683 [astro-ph.CO]];
S. Wang, X. D. Li and M. Li, Phys. Rev. D **82**, 103006 (2010) [arXiv:1005.4345 [astro-ph.CO]].

[19] M. A. Dantas, J. S. Alcaniz, D. Jain and A. Dev, Astron. Astrophys. **467**, 421 (2007) [arXiv:astro-ph/0607060].

[20] S. Capozziello, P. K. S. Dunsby, E. Piedipalumbo and C. Rubano, arXiv:0706.2615 [astro-ph].

[21] M. S. Movahed, S. Baghram and S. Rahvar, Phys. Rev. D **76**, 044008 (2007) [arXiv:0705.0889 [astro-ph]].

[22] M. S. Movahed, M. Farhang and S. Rahvar, Int. J. Theor. Phys. **48**, 1203 (2009) [arXiv:astro-ph/0701339];
M. S. Movahed and S. Ghassemi, Phys. Rev. D **76**, 084037 (2007) [arXiv:0705.3894 [astro-ph]];
N. Pires, Z. H. Zhu and J. S. Alcaniz, Phys. Rev. D **73**, 123530 (2006) [arXiv:astro-ph/0606689].

[23] S. Rahvar and M. S. Movahed, Phys. Rev. D **75**, 023512 (2007) [arXiv:astro-ph/0604206].

[24] S. Wang and Y. Zhang, Phys. Lett. B **669**, 201 (2008) [arXiv:0809.3627 [astro-ph]];
M. L. Tong and Y. Zhang, Phys. Rev. D **80**, 023503 (2009) [arXiv:0906.3646 [gr-qc]].

[25] H. Wei and S. N. Zhang, Phys. Rev. D **76**, 063003 (2007) [arXiv:0707.2129 [astro-ph]];
J. Cui and X. Zhang, Phys. Lett. B **690**, 233 (2010) [arXiv:1005.3587 [astro-ph.CO]].

[26] Y. Zhang, H. Li, X. Wu, H. Wei and R. G. Cai, arXiv:0708.1214 [astro-ph].

[27] E. Witten, arXiv:hep-ph/0002297.

[28] G. ’t Hooft, arXiv:gr-qc/9310026;
L. Susskind, J. Math. Phys. **36**, 6377 (1995) [arXiv:hep-th/9409089];
R. Bousso, Rev. Mod. Phys. **74**, 825 (2002) [arXiv:hep-th/0203101].

[29] A. G. Cohen, D. B. Kaplan and A. E. Nelson, Phys. Rev. Lett. **82**, 4971 (1999) [arXiv:hep-th/9803132];
S. D. H. Hsu, Phys. Lett. B **594**, 13 (2004) [arXiv:hep-th/0403052].

[30] M. Li, Phys. Lett. B **603**, 1 (2004) [arXiv:hep-th/0403127].

[31] X. Zhang and F. Q. Wu, Phys. Rev. D **72**, 043524 (2005) [arXiv:astro-ph/0506310];
X. Zhang and F. Q. Wu, Phys. Rev. D **76**, 023502 (2007) [arXiv:astro-ph/0701405];
Q. G. Huang and Y. G. Gong, JCAP **0408**, 006 (2004) [arXiv:astro-ph/0403590];
Z. Chang, F. Q. Wu and X. Zhang, Phys. Lett. B **633**, 14 (2006) [arXiv:astro-ph/0509531].

[32] Q. G. Huang and M. Li, JCAP **0408**, 013 (2004) [arXiv:astro-ph/0404229];
Q. G. Huang and M. Li, JCAP **0503**, 001 (2005) [arXiv:hep-th/0410095];
X. Zhang, Int. J. Mod. Phys. D **14**, 1597 (2005) [arXiv:astro-ph/0504586];
X. Zhang, Phys. Rev. D **74**, 103505 (2006) [arXiv:astro-ph/0609699];

Y. Z. Ma and X. Zhang, Phys. Lett. B **661**, 239 (2008) [arXiv:0709.1517 [astro-ph]];

X. Wu and Z. H. Zhu, Phys. Lett. B **660**, 293 (2008) [arXiv:0712.3603 [astro-ph]];

J. Zhang, X. Zhang and H. Liu, Eur. Phys. J. C **52**, 693 (2007) [arXiv:0708.3121 [hep-th]];

Y. G. Gong, Phys. Rev. D **70**, 064029 (2004) [arXiv:hep-th/0404030];

B. Wang, E. Abdalla and R. K. Su, Phys. Lett. B **611**, 21 (2005) [arXiv:hep-th/0404057];

X. Wu, R. G. Cai and Z. H. Zhu, Phys. Rev. D **77**, 043502 (2008) [arXiv:0712.3604 [astro-ph]];

M. Li, X. D. Li, C. Lin and Y. Wang, Commun. Theor. Phys. **51**, 181 (2009) [arXiv:0811.3332 [hep-th]];

B. Wang, Y. G. Gong and E. Abdalla, Phys. Lett. B **624**, 141 (2005) [arXiv:hep-th/0506069];

B. Wang, C. Y. Lin and E. Abdalla, Phys. Lett. B **637**, 357 (2006) [arXiv:hep-th/0509107];

X. Zhang, Phys. Lett. B **683**, 81 (2010) [arXiv:0909.4940 [gr-qc]];

D. J. Liu, H. Wang and B. Yang, Phys. Lett. B **694**, 6 (2010) [arXiv:1009.3776 [astro-ph.CO]].

[33] R. G. Cai, Phys. Lett. B **657**, 228 (2007) [arXiv:0707.4049 [hep-th]].

[34] F. Károlyházy, Nuovo Cim. A **42**, 390 (1966);

F. Károlyházy, A. Frenkel and B. Lukács, in *Physics as Natural Philosophy*, edited by A. Simony and H. Feschbach, MIT Press, Cambridge, MA (1982);

F. Károlyházy, A. Frenkel and B. Lukács, in *Quantum Concepts in Space and Time*, edited by R. Penrose and C. J. Isham, Clarendon Press, Oxford, (1986).

[35] H. Wei and R. G. Cai, Phys. Lett. B **660**, 113 (2008) [arXiv:0708.0884 [astro-ph]].

[36] H. Wei and R. G. Cai, Phys. Lett. B **663**, 1 (2008) [arXiv:0708.1894 [astro-ph]];

M. Li, X. D. Li, S. Wang and X. Zhang, JCAP **0906**, 036 (2009) [arXiv:0904.0928 [astro-ph.CO]];

M. Li, X. D. Li and X. Zhang, Sci. China Phys. Mech. Astron. **53**, 1631 (2010) [arXiv:0912.3988 [astro-ph.CO]];

H. Wei, JCAP **1008**, 020 (2010) [arXiv:1004.4951 [astro-ph.CO]];

J. Zhang, L. Zhang and X. Zhang, Phys. Lett. B **691**, 11 (2010) [arXiv:1006.1738 [astro-ph.CO]].

[37] I. P. Neupane, Phys. Rev. D **76**, 123006 (2007) [arXiv:0709.3096 [hep-th]];

J. Zhang, X. Zhang and H. Liu, Eur. Phys. J. C **54**, 303 (2008) [arXiv:0801.2809 [astro-ph]];

Y. W. Kim, H. W. Lee, Y. S. Myung and M. I. Park, Mod. Phys. Lett. A **23**, 3049 (2008) [arXiv:0803.0574 [gr-qc]];

J. P. Wu, D. Z. Ma and Y. Ling, Phys. Lett. B **663**, 152 (2008) [arXiv:0805.0546 [hep-th]];

J. Cui, L. Zhang, J. Zhang and X. Zhang, Chin. Phys. B **19**, 019802 (2010) [arXiv:0902.0716 [astro-ph.CO]];

X. L. Liu and X. Zhang, Commun. Theor. Phys. **52**, 761 (2009) [arXiv:0909.4911 [astro-ph.CO]];

X. L. Liu, J. Zhang and X. Zhang, Phys. Lett. B **689**, 139 (2010) [arXiv:1005.2466 [gr-qc]];

M. R. Setare, Astrophys. Space Sci. **326**, 27 (2010) [arXiv:0908.0196 [gr-qc]];

A. Sheykhi and M. R. Setare, Int. J. Theor. Phys. **49**, 2777 (2010) [arXiv:1003.1109 [physics.gen-ph]];

M. Jamil and E. N. Saridakis, JCAP **1007**, 028 (2010) [arXiv:1003.5637 [physics.gen-ph]];

K. Karami, A. Sheykhi, M. Jamil, Z. Azarmi and M. M. Soltanzadeh, arXiv:1004.3607 [hep-th];

M. Malekjani and A. Khodam-Mohammadi, arXiv:1004.1017 [gr-qc].

[38] D. Pavon and B. Wang, Gen. Rel. Grav. **41**, 1 (2009) [arXiv:0712.0565 [gr-qc]].

[39] S. H. Pereira and J. F. Jesus, Phys. Rev. D **79**, 043517 (2009) [arXiv:0811.0099 [astro-ph]].

[40] F. E. M. Costa, E. M. . Barboza and J. S. Alcaniz, Phys. Rev. D **79**, 127302 (2009) [arXiv:0905.0672 [astro-ph.CO]].

[41] R. G. Cai and Q. Su, Phys. Rev. D **81**, 103514 (2010) [arXiv:0912.1943 [astro-ph.CO]].

[42] C. Y. Sun, arXiv:1009.1214 [gr-qc].

[43] L. Zhang, J. Cui, J. Zhang and X. Zhang, Int. J. Mod. Phys. D **19**, 21 (2010) [arXiv:0911.2838 [astro-ph.CO]].

[44] R. Amanullah *et al.*, Astrophys. J. **716**, 712 (2010) [arXiv:1004.1711 [astro-ph.CO]].

[45] S. Nesseris and L. Perivolaropoulos, Phys. Rev. D **72**, 123519 (2005) [arXiv:astro-ph/0511040];
L. Perivolaropoulos, Phys. Rev. D **71**, 063503 (2005) [arXiv:astro-ph/0412308];
S. Nesseris and L. Perivolaropoulos, JCAP **0702**, 025 (2007) [arXiv:astro-ph/0612653].

[46] Y. Wang and P. Mukherjee, Astrophys. J. **650**, 1 (2006) [arXiv:astro-ph/0604051].

[47] J. R. Bond, G. Efstathiou and M. Tegmark, Mon. Not. Roy. Astron. Soc. **291**, L33 (1997) [arXiv:astro-ph/9702100].

[48] E. Komatsu *et al.*, arXiv:1001.4538 [astro-ph.CO].

[49] M. Tegmark *et al.* [SDSS Collaboration], Astrophys. J. **606**, 702 (2004) [arXiv:astro-ph/0310725];
U. Seljak *et al.* [SDSS Collaboration], Phys. Rev. D **71**, 103515 (2005) [arXiv:astro-ph/0407372];
M. Tegmark *et al.* [SDSS Collaboration], Phys. Rev. D **74**, 123507 (2006) [arXiv:astro-ph/0608632].

[50] D. J. Eisenstein *et al.* [SDSS Collaboration], Astrophys. J. **633**, 560 (2005) [arXiv:astro-ph/0501171].