Interacting agegraphic dark energy model in tachyon cosmology coupled to matter

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ABSTRACT

Scalar-field dark energy models for tachyon fields are often regarded as an effective description of an underlying theory of dark energy. In this Letter, we propose the agegraphic dark energy model in tachyon cosmology by interaction between the components of the dark sectors. In the formalism, the interaction term emerges from the tachyon field nonminimally coupled to the matter Lagrangian in the model rather than being inserted into the formalism as an external source. The model is constrained by the observational data. Based on the best fitted parameters in both original and new agegraphic dark energy scenarios, the model is tested by Sne Ia data. The tachyon potential and tachyon field are reconstructed and coincidence problem is revisited.

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1. Introduction

A great variety of cosmological observations, direct and indirect, reveal that our universe is currently undergoing a phase of accelerated expansion [1]. A component which causes cosmic acceleration is usually dubbed dark energy (DE) which is part of a mysterious puzzle in modern cosmology. The most obvious theoretical candidate of DE is the cosmological constant, where it suffers from fine-tuning and cosmic-coincidence problems [2]. Among other candidates for probing the nature of DE, the holographic dark energy (HDE) model and agegraphic dark energy (ADE), both appear to be consistent with quantum kinematics, in the sense that obey the Heisenberg type uncertainty relation and predict a time-varying DE equation of state (EoS). In HDE models one chooses the event horizon of the universe as the length scale, where HDE gives the observation value of DE in the universe and can drive the universe to an accelerated expansion phase. The HDE models are very successful in explaining the observational data and has been studied widely [3–8]. However, an obvious drawback concerning causality appears in these models by choosing event horizon as the length scale. Event horizon is a global concept of spacetime; its existence depends on future evolution of the universe; and exists only for universe with forever accelerated expansion. In addition, more recently, it has been argued that this proposal might be in contradiction to the age of some old high redshift objects, unless a lower Hubble parameter is considered [9]. More recently, a new DE model, dubbed "agegraphic dark energy" model, has been proposed by Cai [10], which is also related to the holographic principle of quantum gravity. The agegraphic dark energy takes into account the uncertainty relation of quantum mechanics together with the gravitational effect in general relativity [11–14]. Since in ADE model the age of the universe is chosen as the length measure, instead of the horizon distance, the causality problem in the holographic dark energy is avoided. The agegraphic models of DE have been examined and constrained by various astronomical observations [15]. Although going along a fundamental theory such as quantum gravity may provide a hopeful way towards understanding the nature of DE, it is hard to believe that the physical foundation of ADE is convincing enough. Though, under such circumstances, the models of holographic and ADE, to some extent, still have some advantage comparing to other dynamical DE models because at least they originate from some fundamental principles in quantum gravity [16].

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For the first time, the authors in [17] study the interaction between HDE and DM in IHDE models, based on phenomenological grounds, with the aim to alleviate the coincidence problem.

In general, the interacting terms in IADE models are not unique. Here, we would like to extend the previous work carried in the IADE models, by studying a tachyon cosmological model in which the scalar field in the formalism plays two roles: as a scalar field interacts with the matter in the universe and as a tachyon field plays the role of DE. In our formalism the interacting term naturally appears in the model from the interaction between scalar field and matter field in the universe. We consider the cosmological model in the presence of with a tachyon potential and a nonminimally scalar field coupled to the matter Lagrangian in the action given by [18,19],

$$S = \int \left[\frac{M_p^2 R}{2} - V(\phi)\sqrt{1 - \partial_\mu \phi \partial^\mu \phi} + f(\phi)\mathcal{L}_m \right] \sqrt{-g}d^4x, \quad (1.1)$$

where R is Ricci scalar. Unlike the usual Einstein–Hilbert action, the matter Lagrangian $\mathcal{L}_m$ is modified as $f(\phi)\mathcal{L}_m$, where $f(\phi)$ is an analytic function of ϕ. This last term in Lagrangian brings about the nonminimal interaction between the matter and the scalar field. It was demonstrated that DE driven by tachyon, decays to CDM in the late accelerated universe and this phenomenon yields a solution to cosmic coincidence problem. In fact, one of the motivation to include the interaction between dark energy and dark matter is to solve the coincidence problem [20,21]. The investigations on the reconstruction of the tachyon potential $V(\phi)$ in the framework of ADE have been carried out in [22]. In the present Letter, we would like to extend the study to the case where both components – the pressureless CDM and the ADE – do not conserve separately but interact with each other. Given the unknown nature of both DM and DE there is nothing in principle against their mutual interaction and it seems very special that these two major components in the universe are entirely independent. We suggest the agegraphic description of the tachyon DE in a universe and reconstruct the potential and the dynamics of the tachyon scalar field which describe the tachyon cosmology.

2. Tachyon reconstruction of the original ADE

The variation of action (1.1) with respect to the metric tensor components in a spatially flat FRW cosmology yields the following field equations,

$$3H^2 M_p^2 = \rho_m f + \frac{V(\phi)}{\sqrt{1 - \dot{\phi}^2}}, \quad (2.1)$$

$$M_p^2 (2\dot{H} + 3H^2) = -\gamma \rho_m f + V(\phi)\sqrt{1 - \dot{\phi}^2}, \quad (2.2)$$

where $H = \frac{\dot{a}}{a}$ is the Hubble parameter. In the above, we also assumed a perfect fluid filled the universe with the equation of state $p_m = \gamma \rho_m$. In the following we assume that the matter in the universe is CMD where $\gamma = 0$. We can rewrite the above equations as

$$3H^2 M_p^2 = \rho_m f + \rho_{tac}, \quad (2.3)$$

$$M_p^2 (2\dot{H} + 3H^2) = -p_m f - p_{tac}, \quad (2.4)$$

where ρ_{tac} and p_{tac} are respectively the energy density and pressure of the tachyon field. We define the fractional energy densities such as

$$\Omega_{mf} = \frac{\rho_m f}{3M_p^2 H^2}, \qquad \Omega_{tac} = \frac{\rho_{tac}}{3M_p^2 H^2}, \quad (2.5)$$

where "mf" and "tac" stand for nonminimally coupled scalar field to matter Lagrangian and tachyon, where $\Omega_{mf} = \Omega_m f$. Thus, the Friedmann equation can be written as

$$\Omega_{mf} + \Omega_{tac} = 1. \quad (2.6)$$

Next we intend to implement the interacting original ADE models with tachyon scalar field. Let us first review the origin of the ADE model. Following the line of quantum fluctuations of spacetime, Karolyhazy et al. [23] argued that the distance t in Minkowski spacetime cannot be known to a better accuracy than $\delta t = \beta t_p^{2/3} t^{1/3}$ where β is a dimensionless constant of order unity. Based on Karolyhazy relation, Maziashvili discussed that the energy density of metric fluctuations of the Minkowski spacetime is given by [24,25]

$$\rho_D \sim \frac{1}{t_p^2 t^2} \sim \frac{M_p^2}{t^2}, \quad (2.7)$$

where t_p is the reduced Planck time and t is a proper time scale. In the original ADE model Cai [10] proposed the DE density of the form (2.7) where t is chosen to be the age of the universe

$$T = \int_0^a \frac{da}{Ha}. \quad (2.8)$$

Thus, he wrote down the energy density of the original ADE as

$$\rho_D = \frac{3n^2 M_p^2}{T^2}, \quad (2.9)$$

where the numerical factor $3n^2$ is introduced to parameterize some uncertainties, such as the species of quantum fields in the universe, the effect of curved spacetime, and so on. The dark energy density (2.9) has the same form as the HDE, but the length measure is chosen to be the age of the universe instead of the horizon radius of the universe. Thus the causality problem in the agegraphic dark energy is avoided. Combining Eqs. (2.9) and (2.5), we get

$$\Omega_D = \frac{n^2}{T^2 H^2}. \quad (2.10)$$

If we assume that the scalar field as a tachyon field plays the role of ADE and as a nonminimally coupled field plays the role of DM, then with the interaction between these two fields their energy densities no longer satisfy independent conservation laws, instead they obey:

$$\dot{\rho}_{mf} + 3H\rho_{mf} = Q, \quad (2.11)$$

$$\dot{\rho}_{tac} + 3H(1 + \omega_{tac})\rho_{tac} = -Q, \quad (2.12)$$

where $\rho_{mf} = \rho_m f$ and $Q = \rho_m \dot{f}$ is the interaction term. In Q, $\dot{f}$ gauges the intensity of the coupling between matter and scalar field. For $\dot{f} = 0$, there is no interaction between DM and ADE. The Q term measures the different evolution of the DM due to its interaction with the ADE which gives rise to a different universe expansion. The interesting point concerning the interaction term is that in comparison to the other agegraphic models where the form of the interaction term Q is not unique and usually is expressed as $Q = 3b^2 H(\rho_m + \rho_{DE})$, in our model the interaction term naturally appears in the model directly as a function of the scalar field coupling function $f(\phi)$ and ρ_m and indirectly as a function of Hubble parameter H and ρ_{tac}. Taking the derivative with respect to the cosmic time of Eq. (2.9) and using Eq. (2.10) we get

$$\dot{\rho}_D = -2H\rho_D \frac{\sqrt{\Omega_D}}{n}. \quad (2.13)$$

Inserting this relation into Eq. (2.12), we obtain the EoS parameter of the original ADE in flat universe

$$\omega_D = -1 + \frac{2\sqrt{\Omega_D}}{3n} - \frac{Q}{3H\rho_D}. \tag{2.14}$$

Differentiating Eq. (2.10) and using relation $\dot{\Omega}_D = \Omega'_D H$, we reach

$$\Omega'_D = \Omega_D\left(-2\frac{\dot{H}}{H^2} - \frac{2\sqrt{\Omega_D}}{n}\right), \tag{2.15}$$

where the dot and the prime stand for the derivative with respect to the cosmic time and $x = \ln a$, respectively. Taking the derivative of both sides of the Friedmann equation (2.3) with respect to the cosmic time, and using Eqs. (2.6), (2.9), (2.10) and (2.11), it is easy to show that

$$\frac{\dot{H}}{H^2} = -\frac{3}{2}\left(1 + \Omega_D\left(-1 + \frac{2\sqrt{\Omega_D}}{3n} - \frac{Q}{3H\rho_D}\right)\right). \tag{2.16}$$

Substituting this relation into Eq. (2.15), we obtain the equation of motion for the original ADE as

$$\Omega'_D = \Omega_D(1 - \Omega_D)\left(3 - \frac{2\sqrt{\Omega_D}}{n}\right) - \frac{\Omega_m \Omega_D \dot{f}}{H}. \tag{2.17}$$

By using relation $\frac{d}{dx} = -(1+z)\frac{d}{dz}$ we can express Ω_D as

$$\frac{d\Omega_D}{dz} = -(1+z)^{-1}\left(\Omega_D(1 - \Omega_D)\left(3 - \frac{2\sqrt{\Omega_D}}{n}\right) - \frac{\Omega_m \Omega_D \dot{f}}{H}\right). \tag{2.18}$$

Now we suggest a correspondence between the original ADE and tachyon scalar field namely, we identify ρ_{tac} with ρ_D. Using relation $\rho_{tac} = \rho_D = 3H^2 M_p^2 \Omega_D$ and $\omega_D = \dot{\phi}^2 - 1$, we can find

$$V(\phi) = \rho_{tac}\sqrt{1 - \dot{\phi}^2} = 3H^2 M_p^2 \Omega_D\left(1 - \frac{2\sqrt{\Omega_D}}{3n} + \frac{Q}{3H\rho_D}\right)^{1/2}, \tag{2.19}$$

$$\dot{\phi} = \sqrt{1 + \omega_D} = \left(\frac{2\sqrt{\Omega_D}}{3n} - \frac{Q}{3H\rho_D}\right)^{1/2}. \tag{2.20}$$

Using relation $\dot{\phi} = \phi' H$, we get

$$\phi' = H^{-1}\left(\frac{2\sqrt{\Omega_D}}{3n} - \frac{Q}{3H\rho_D}\right)^{1/2}, \tag{2.21}$$

or equivalently

$$\frac{d\phi}{dz} = \frac{1}{H(1+z)}\left(\frac{2\sqrt{\Omega_D}}{3n} + \frac{Q}{3H\rho_D}\right)^{1/2}. \tag{2.22}$$

Also by using Eq. (2.16) we can write

$$\frac{dH}{dz} = -H(1+z)^{-1}\left(\frac{3\Omega_D}{2} - \frac{\Omega_D^{3/2}}{n} - \frac{3}{2} - \frac{\Omega_m \dot{f}}{2H}\right), \tag{2.23}$$

where the sign is arbitrary and can be changed by a redefinition of the field, $\phi \to -\phi$. Then, by fixing the field amplitude at the present era to be zero, one can easily obtain the dynamic of the agegraphic tachyon field. It is difficult to solve Eqs. (2.18), (2.22) and (2.23) analytically, however, the evolutionary form of the interacting agegraphic tachyon field ϕ and Ω_{tac} can be easily obtained integrating it numerically from $z = 0$ to a given value z. In addition, from the constructed agegraphic tachyon model, the evolution of $V(\phi)$ with respect to ϕ can be determined. In the following, we assume that the function $f(\phi)$ behaves exponentially as $f(\phi) = f_0 e^{b\phi(z)}$. Since $\dot{f}(\phi)$ is present in the interaction

term Q, the parameters that determine the dynamics of the interaction are b and f_0 together with ρ_m and γ, the energy density and EoS parameter of the matter, respectively. Note that $f_0 = 0$ or $b = 0$ leads to the absence of the interaction. We will do numerical calculation after the best fit analyzing of our model in Section 4.

3. Tachyon reconstruction of the new ADE

To avoid some internal inconsistencies in the original ADE model, the so-called "new agegraphic dark energy" was proposed, where the time scale is chosen to be the conformal time η instead of the age of the universe. The new ADE contains some new features different from the original ADE and overcome some unsatisfactory points. For instance, the original ADE suffers from the difficulty to describe the matter-dominated epoch while the new ADE resolved this issue [26]. The energy density of the new ADE can be written as

$$\rho_D = \frac{3n^2 M_p^2}{\eta^2}, \tag{3.1}$$

where the conformal time η is given by

$$\eta = \int_0^a \frac{da}{Ha^2}. \tag{3.2}$$

The fractional energy density of the new ADE is now expressed as

$$\Omega_D = \frac{n^2}{H^2 \eta^2}. \tag{3.3}$$

Taking the derivative with respect to the cosmic time of Eq. (3.1) and using Eq. (3.3) we get

$$\dot{\rho}_D = -2H\frac{\sqrt{\Omega_D}}{na}\rho_D. \tag{3.4}$$

Inserting this relation into Eq. (2.12) we obtain the EoS parameter of the new ADE

$$\omega_D = -1 + \frac{2\sqrt{\Omega_D}}{3na} - \frac{Q}{3H\rho_D}. \tag{3.5}$$

The evolution behavior of the new ADE is now given by

$$\Omega'_D = \Omega_D(1 - \Omega_D)\left(3 - \frac{2\sqrt{\Omega_D}}{na}\right) - \frac{\Omega_m \Omega_D \dot{f}}{H}, \tag{3.6}$$

or equivalently

$$\frac{d\Omega_D}{dz} = -(1+z)^{-1}\left(\Omega_D(1 - \Omega_D)\left(3 - \frac{2\sqrt{\Omega_D}}{na}\right) - \frac{\Omega_m \Omega_D \dot{f}}{H}\right). \tag{3.7}$$

Next, we reconstruct the new agegraphic tachyon DE model, connecting the tachyon scalar field with the new ADE. Using Eqs. (3.3) and (3.5) one can easily show that the tachyon potential and kinetic energy term take the following form

$$V(\phi) = 3H^2 M_p^2 \Omega_D\left(1 - \frac{2\sqrt{\Omega_D}}{3na} + \frac{Q}{3H\rho_D}\right)^{1/2}, \tag{3.8}$$

$$\dot{\phi} = \left(\frac{2\sqrt{\Omega_D}}{3na} - \frac{Q}{3H\rho_D}\right)^{1/2}. \tag{3.9}$$

Table 1
Best fit values of original ADE model.

Observational data	$H(z)$	$H(z) + CMB$	$H(z) + CMB + BAO$
$H(0)$ (Km/s/Mpc)	71	71	72
$\Omega_D(0)$	0.72	0.73	0.73
n	18.6	7.2	22.2
b	−0.7	0.2	−0.4

Table 2
Best fit values of NADE model.

Observational data	$H(z)$	$H(z) + CMB$	$H(z) + CMB + BAO$
$H(0)$ (Km/s/Mpc)	71	71	72
$\Omega_D(0)$	0.72	0.73	0.73
n	24	8.3	38.3
b	−0.9	0.3	−0.6

We can also rewrite Eq. (3.9) as

$$\phi' = H^{-1}\left(\frac{2\sqrt{\Omega}_D}{3na} - \frac{Q}{3H\rho_D}\right)^{1/2}, \tag{3.10}$$

or

$$\frac{d\phi}{dz} = \frac{1}{H(1+z)}\left(\frac{2\sqrt{\Omega}_D}{3na} + \frac{Q}{3H\rho_D}\right)^{1/2}. \tag{3.11}$$

In this way we connect the interacting new ADE with a tachyon field and reconstruct the potential and the dynamics of the tachyon field which describe tachyon cosmology. Similar to Eq. (2.23), for new ADE we can write

$$\frac{dH}{dz} = -H(1+z)^{-1}\left(\frac{3\Omega_D}{2} - \frac{\Omega_D^{3/2}}{na} - \frac{3}{2} - \frac{\Omega_m\dot{f}}{2H}\right). \tag{3.12}$$

Again, it is difficult to solve Eqs. (3.7), (3.11) and (3.12) analytically, however, the evolutionary form of the interacting new agegraphic tachyon field ϕ and Ω_{tac} can be easily obtained by integrating it numerically from $z = 0$ to a given value z. In addition, from the constructed agegraphic tachyon model, the evolution of $V(\phi)$ with respect to ϕ can be determined.

4. Observational best fitting with Hubble parameter, $H(z)$

Now, we study the constraints on the model parameters using χ^2 method, utilizing recent observational data, including the Hubble parameter as a function of the redshift, the baryonic acoustic oscillation (BAO) distance ratio and the cosmic microwave background (CMB) radiation.

We solve the set of coupled nonlinear partial differential equations, (2.18), (2.22), (2.23). For best fitting the model for the parameters n, b and the initial conditions $\Omega_D(0)$ and $H(0)$ with the most recent observational data for Hubble parameter, we employ the χ^2 method. We constrain the parameters including the initial conditions by minimizing the χ^2 function given as

$$\chi^2_{Hub}\big(n, b; \Omega_D(0), H(0)\big)$$
$$= \sum_{i=1}^{14} \frac{[H^{th}(z_i|n, b; \Omega_D(0), H(0)) - H^{obs}(z_i)]^2}{\sigma^2_{Hub}(z_i)}, \tag{4.1}$$

where the sum is over the cosmological dataset. In (4.1), H^{th} and H^{obs} are the Hubble parameters obtained from the theoretical model and from observation, respectively. Also, σ_{Hub} is the estimated error of the H^{obs} where obtained from observation [27].
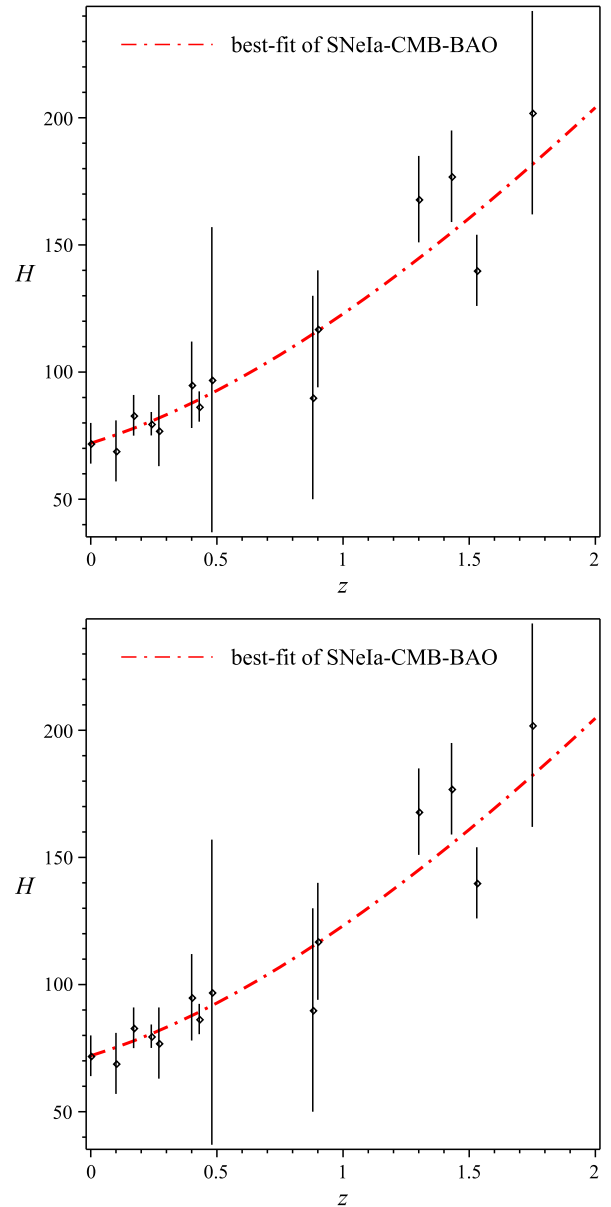

Fig. 1. The best fitted $H(z) + CMB + BAO$, for the original and new ADE model.

We add the CMB data in our analysis. Since the CMB shift parameter R [28,29], contains the main information of the observations from the CMB, it is used to constrain the theoretical models by minimizing

$$\chi^2_{CMB} = \frac{[R - R_{obs}]^2}{\sigma^2_R}, \tag{4.2}$$

where $R_{obs} = 1.725 \pm 0.018$ [30], is given by the WMAP7 data. Its corresponding theoretical value is defined as

$$R \equiv \Omega_{m0}^{1/2} \int_0^{z_{CMB}} \frac{dz'}{E(z')}, \tag{4.3}$$

with $z_{CMB} = 1091.3$. Moreover, for the BAO data, the BAO distance ratio at $z = 0.20$ and $z = 0.35$ from the joint analysis of the 2dF Galaxy Redsihft Survey and SDSS data [31,32] is used. The distance ratio, given by
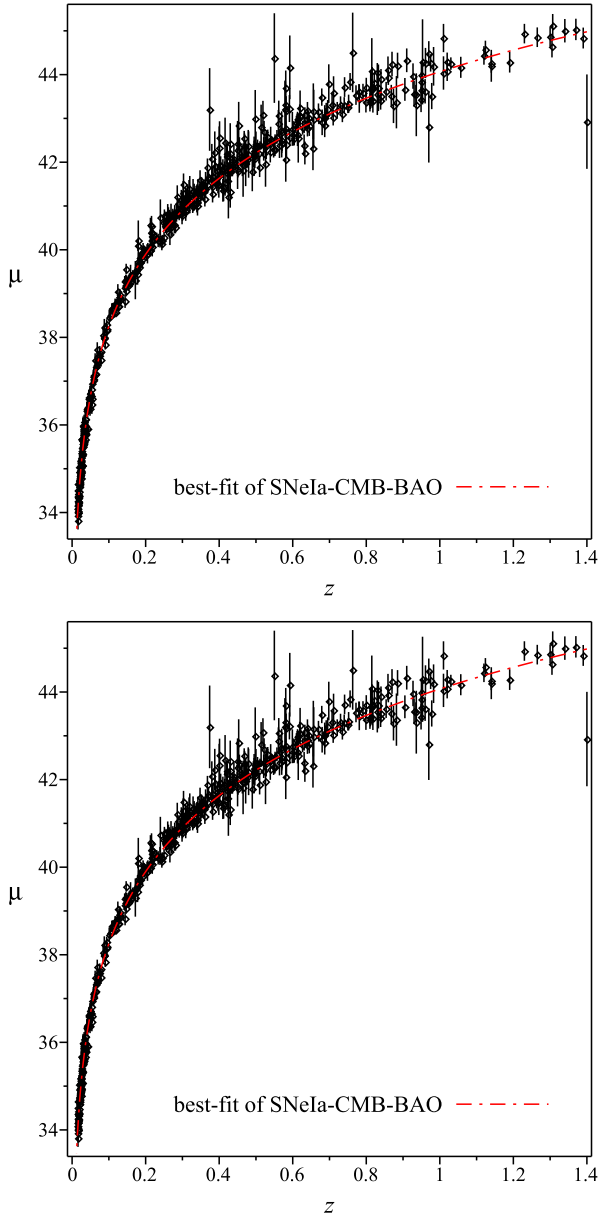
Fig. 2. The best fitted distance modulus for the original and new ADE model.
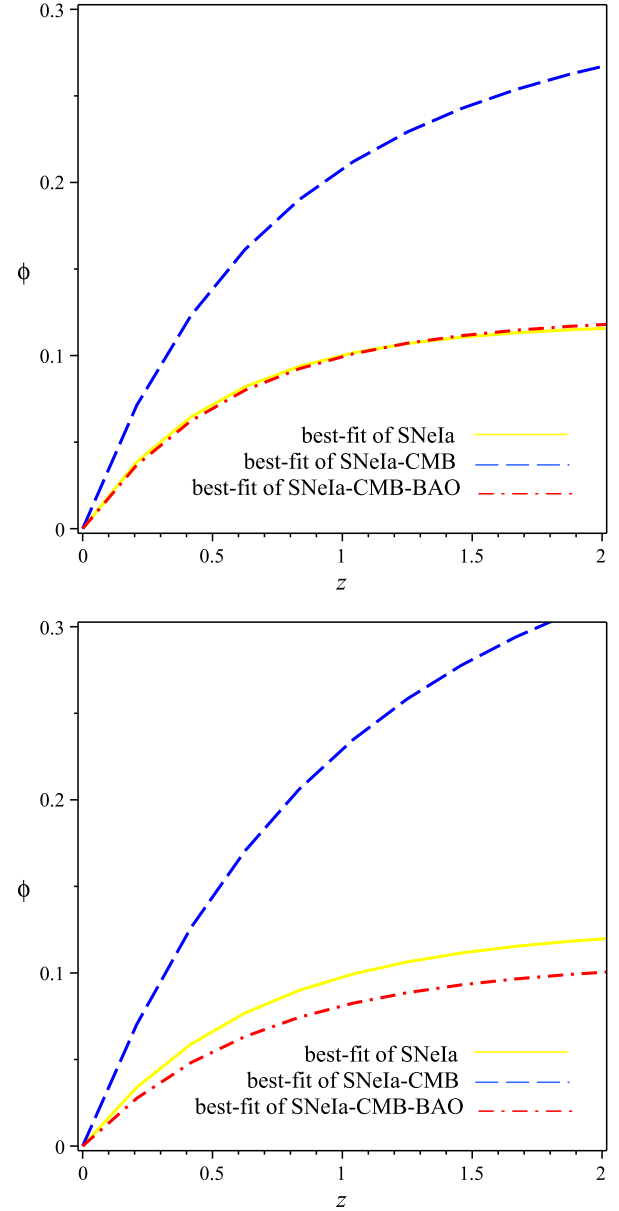

Fig. 3. Yellow (solid), blue (dash) and red (dash–dot) lines show the best fitted $\phi(z)$, respectively, for the original and new ADE model. (For interpretation of the references to color, the reader is referred to the web version of this Letter.)

$$\frac{D_V(z=0.35)}{D_V(z=0.20)} = 1.736 \pm 0.065, \tag{4.4}$$

is a relatively model independent quantity with $D_V(z)$ defined as

$$D_V(z_{BAO}) = \left[\frac{z_{BAO}}{H(z_{BAO})} \left(\int_0^{z_{BAO}} \frac{dz}{H(z)} \right)^2 \right]^{1/3}. \tag{4.5}$$

So, the constraint from BAO can be obtained by performing the following χ^2 statistics

$$\chi^2_{BAO} = \frac{[(D_V(z=0.35)/D_V(z=0.20)) - 1.736]^2}{0.065^2}. \tag{4.6}$$

The constraints from a combination of Sne Ia, BAO and CMB can be obtained by minimizing $\chi^2_{Sne} + \chi^2_{BAO} + \chi^2_{CMB}$ in two original and new ADE scenarios. The results are shown in Tables 1 and 2.

From Tables 1 and 2, and Fig. 1 the results show that the initial conditions for dynamical variables Ω_D and H are not sensitive to the cosmological models of original and new ADE. They are not

also sensitive to the CMB and BAO data. However, the model parameters n and b are very dependent on both cosmological models and observational dataset.

5. Cosmological test

We have already best fitted our model with the current observational data for Hubble parameter. Now, we test our model against recent observational data for the best fitted distance modulus in both original and new ADE, as shown in Fig. 2. The graphs show that the model is in good agreement with the observational data.

In addition for both models we plotted the reconstructed potential and scalar field $V(\phi)$ and $\phi(z)$ respectively using the best fitted model parameters (see Figs. 3 and 4).

In Fig. 3, we see that the dynamics of the best fitted and reconstructed scalar field depends on the observational data and also
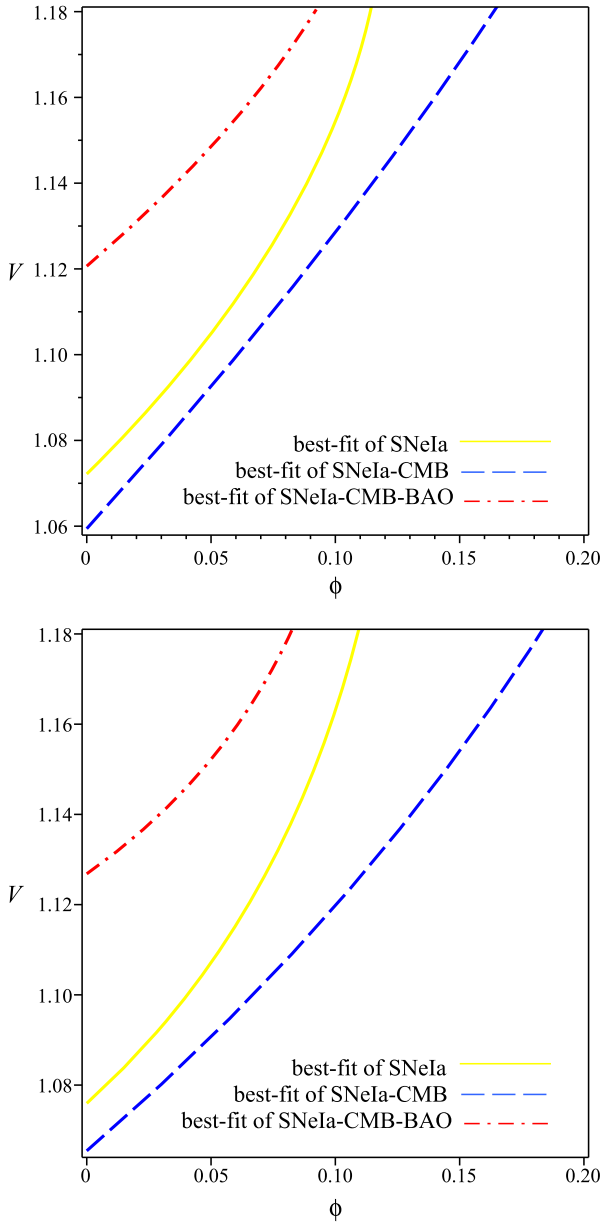
Fig. 4. Yellow (solid), blue (dash) and red (dash–dot) lines show the best fitted $V(\phi)$, respectively, for the original and new ADE model. (For interpretation of the references to color, the reader is referred to the web version of this Letter.)

Fig. 5. Phase space of the scale factor for $\Omega_D = 0.74$ and the best fitted model parameters. At present epoch, we choose $a = 1$; $z = 0$. The transition from decelerated expansion to accelerated one is shown in both old (dashed red) and new (solid black) ADE scenarios. (For interpretation of the references to color, the reader is referred to the web version of this Letter.)

Fig. 6. The behaviors of the ratio $r = \rho_c/\rho_d$ in two cases of old and new ADE scenarios.

cosmological models. The graphs show a decreasing trend with decreasing redshift. Similar behavior can be seen in the graphs for the reconstructed potential function with the best fitted model parameters.

In [33], based on different forms of tachyon potential, the behavior of the scale factor and the duration of the accelerated expansion of the universe is discussed. Here, in Fig. 5, we have plotted the phase portrait for the scale factor in both old and new ADE scenarios. The graph shows that the current tachyon dominated universe creates late time acceleration and earlier dark matter domination produces the deceleration phase in to past. It also illustrates the dynamics of cosmic scale factor in both cases of old and new ADE.

Using the fitting result, we have also studied the coincidence problem. The ratio of energy densities between DM and DE, $r = \rho_{DM}/\rho_D$, and its evolution is plotted with respect to the scale factor in Fig. 6. From the graph we observe a slower change of r in the
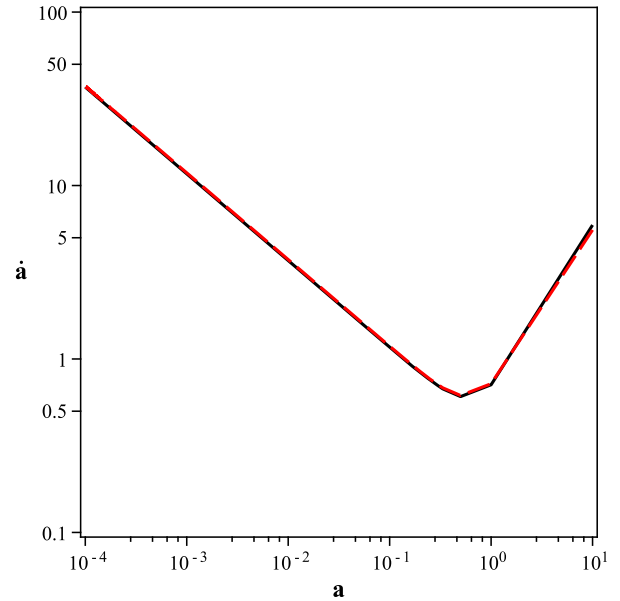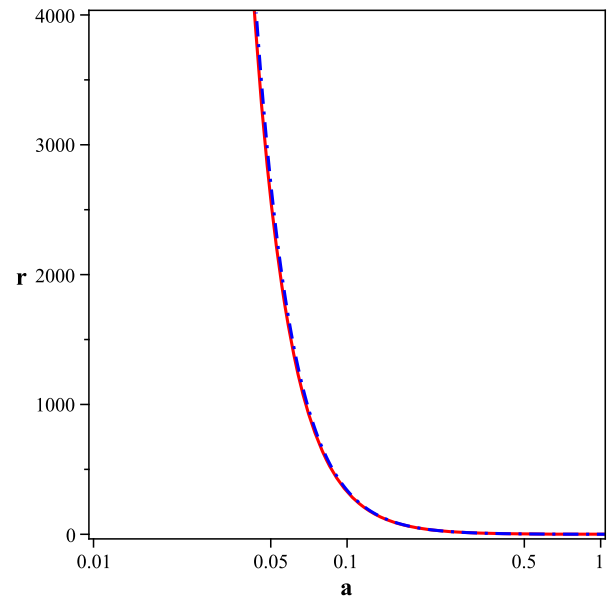
current epoch of the universe expansion in both cases of old and new ADE scenarios. Also, the ratio is about one-to-one in the late time era. In comparison to ΛCDM model, the period when energy densities of DE and DM are comparable is longer due to the interaction between DE and DM, see Fig. 6. This in turn ameliorates the coincidence problem. Similar to the phase space of the scale factor, the ratio of energy densities is not affected by the new ADE model.

6. Summary

In this Letter, we investigate the original and new interacting agegraphic dark energy models in tachyon cosmology. We assume

that the matter field acts as DM and the tachyon filed plays the role of original or new ADE. We also assume that these two dark components interact and the interaction term emerges from the model rather being inserted into the formalism as an external source. We first constraint the model parameters and the initial conditions with the observational data for Hubble parameter using chi-squared statistical method. The result shows that the initial conditions are insensitive to the cosmological models and observational data whereas the model parameters highly depend on them. Then based on the best fitted evolutionary behavior of the interacting original and new ADE, we test the model against observational data for distance modulus and also reconstruct the tachyon potential and scalar field. Further, we compute the scale factor velocity and the ratio of dark sectors with respect to the scale factor of the universe in both scenarios and revisit the coincidence problem.

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