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Avoiding the big-rip jeopardy in a quintom dark energy model with higher derivatives

Xiao-fei Zhang [*], Taotao Qiu

Institute of High Energy Physics, Chinese Academy of Sciences, P.O. Box 918-4, Beijing 100049, PR China

Abstract

In the framework of a single scalar field quintom model with higher derivative, we construct in this Letter a dark energy model of which the equation of state (EOS) w crosses over the cosmological constant boundary. Interestingly during the evolution of the universe $w < -1$ happens just for a period of time with a distinguished feature that w starts with a value above -1, transits into $w < -1$, then comes back to $w > -1$. This avoids the big-rip jeopardy induced by $w < -1$.

1. Introduction

In 1998 the analysis of the redshift-distance relation of type Ia supernova (SNIa) established that our universe is currently accelerating [1,2], which has been further confirmed by recent observations of SNIa at high confidence level [3–5]. Combined with other observations and experiments this strongly indicates that our universe is dominated by a component with a negative pressure, dubbed dark energy, which has been studied widely in the recent years. Various candidates for dark energy, such as cosmological constant, quintessence [6,7], phantom [8] and the model of k-essence with non-canonical kinetic term [9,10], have been proposed.

Though the recent analysis on the data from the Supernova, cosmic microwave background (CMB) and large scale structure (LSS) show that the cosmological constant fits well to the data, the dynamical models of dark energy are generally not excluded, see Ref. [11] for a recent review on dynamical dark energy and actually a class of models, the quintom, with an

EOS w larger than -1 in the past, less than -1 today, and evolving across -1 in the intermediate redshift is mildly favored [12,13].

There have been many increasing activities in the studies on the quintom-like models of dark energy [14–36] in the recent years. For the conventional single scalar field, the EOS w cannot cross over $w = -1$ [37–39] due to the instabilities of dark energy perturbation during evolution. In this Letter we focus on a particular example of the quintom dark energy with a single scalar field and study its cosmological evolution.

The model under investigation is a generalization of the model in Ref. [40] with the Lagrangian given by

$$\mathcal{L} = \mathcal{L}\big(\phi, X, \Box\phi\Box\phi, \nabla_\mu\nabla_\nu\phi\nabla^\mu\nabla^\nu\phi\big). \tag{1}$$

In the Lagrangian (1), $X \equiv \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi$ and $\Box \equiv \nabla_\mu\nabla^\mu$. From (1), it is straightforward to get the equation of motion

$$\frac{\partial\mathcal{L}}{\partial\phi} - \nabla_\mu\left(\frac{\partial\mathcal{L}}{\partial X}\nabla^\mu\phi\right) + \Box\left(\frac{\partial\mathcal{L}}{\partial\Box\phi}\right)$$
$$+ \nabla_\nu\nabla_\mu\left(\frac{\partial\mathcal{L}}{\partial s}\nabla^\mu\nabla^\nu\phi\right) = 0, \tag{2}$$

* Corresponding author.
E-mail addresses: zhangxf@ihep.ac.cn, zhangxf@mail.ihep.ac.cn (X.-f. Zhang), qiutt@ihep.ac.cn (T. Qiu).

and the energy–momentum tensor

$$T^{\mu\nu} = \left[\nabla_\rho \left(\frac{\partial \mathcal{L}}{\partial \Box \phi} \nabla^\rho \phi \right) - \mathcal{L} \right] g^{\mu\nu} + \frac{\partial \mathcal{L}}{\partial X} \nabla^\mu \phi \nabla^\nu \phi$$
$$- \nabla^\mu \left(\frac{\partial \mathcal{L}}{\partial \Box \phi} \right) \nabla^\nu \phi - \nabla^\nu \left(\frac{\partial \mathcal{L}}{\partial \Box \phi} \right) \nabla^\mu \phi$$
$$- \nabla_\rho \left(\frac{\partial \mathcal{L}}{\partial s} \nabla^\mu \nabla^\rho \phi \right) \nabla^\nu \phi - \nabla_\rho \left(\frac{\partial \mathcal{L}}{\partial s} \nabla^\nu \nabla^\rho \phi \right) \nabla^\mu \phi$$
$$+ \nabla_\rho \left(\frac{\partial \mathcal{L}}{\partial s} \nabla^\mu \nabla^\nu \phi \right) \nabla^\rho \phi, \tag{3}$$

where s is defined as

$$s \equiv \frac{1}{2} \nabla_\mu \nabla_\nu \phi \nabla^\mu \nabla^\nu \phi. \tag{4}$$

This model for the moment is just an effective theory and we assume that the operators associated with the higher derivatives can be derived from some fundamental theories, for instance due to the quantum corrections or the non-local physics in the string theory [41–43]. In addition, with the higher derivative terms to the Einstein gravity, the theory is shown to be renormalizable [44] which has attracted many attentions. Recently, higher derivative operators have been considered to stabilize the linear fluctuations in the scenario of "ghost condensation" [45].

In Ref. [40], the authors studied in detail a specific model which is equivalent to the uncoupled two-field model (one is the quintessence-like and the other is the phantom-like) and gave rise to the fate of the universe dominated by the phantom-like field, as was implied in two-field quintom model [12,14–18]. Thus the universe might face some problems such as ending in "big-rip" [46] (there are some other possibilities of the fate of phantom universe, see [47–50]). In this Letter, however, we generalize this kind of model and show some new possibilities of the cosmological evolution. Specifically we will show that in our case there is a possibility that $w < -1$ happens just for a period of time. Hence in this scenario it is free of the big-rip jeopardy.

2. Models with higher derivative

Consider the Lagrangian with the following form

$$\mathcal{L} = \frac{1}{2} A(\phi) \nabla_\mu \phi \nabla^\mu \phi + \frac{C(\phi)}{2 M_{\text{pl}}^2} (\Box \phi)^2 - V(\phi). \tag{5}$$

As proved explicitly in [40], such a model is classically equivalent to a two-field model. This is consistent with the general result stated by Ostrogradsky theorem (a nice review on this theorem can be found in [51]) that higher derivative theory brings more degrees of freedom. For the purpose of seeing how the model in (5) is equivalent to two-field model, we introduce an auxiliary field χ and a new Lagrangian,

$$\mathcal{L}' = \frac{1}{2} A(\phi) \nabla_\mu \phi \nabla^\mu \phi - \nabla_\mu \phi \nabla^\mu \chi - \frac{M_{\text{pl}}^2 \chi^2}{2 C(\phi)} - V(\phi). \tag{6}$$

Through the variation on χ, one can see that

$$\chi = \frac{C(\phi)}{M_{\text{pl}}^2} \Box \phi. \tag{7}$$

By substituting it into (6) and dropping out a total derivative, the new Lagrangian (6) reduces exactly to the old one (5). But the former has the form of two-field without higher derivatives. This is more clearly by further field transformations. Consider the field ϕ as a function of two independent scalar fields χ and ψ. Using the transformation

$$\phi = \phi(\psi, \chi), \tag{8}$$

Eq. (6) can be written as

$$\mathcal{L}' = \frac{1}{2} A(\phi) \left(\frac{\partial \phi}{\partial \psi} \right)^2 \nabla_\mu \psi \nabla^\mu \psi - \frac{1}{2} A(\phi) \left(\frac{\partial \phi}{\partial \chi} \right)^2 \nabla_\mu \chi \nabla^\mu \chi$$
$$- \frac{M_{\text{pl}}^2 \chi^2}{2 C(\phi)} - V[\phi(\psi, \chi)], \tag{9}$$

as long as the transformation (8) satisfies

$$A(\phi) \frac{\partial \phi}{\partial \chi} = 1. \tag{10}$$

So the model in (5) is equivalent to the two-field model (9). The kinetic terms of ψ and χ have to take opposite signs and one of them must be ghost, which depends on the sign of $A(\phi)$. Furthermore, we can choose ϕ as a function of $\psi + \chi$ and set

$$A(\phi) \frac{\partial \phi}{\partial \psi} = 1. \tag{11}$$

So, we get a more elegant form for the Lagrangian

$$\mathcal{L}' = \frac{1}{2 A[\phi(\psi + \chi)]} \nabla_\mu \psi \nabla^\mu \psi - \frac{1}{2 A[\phi(\psi + \chi)]} \nabla_\mu \chi \nabla^\mu \chi$$
$$- \frac{M_{\text{pl}}^2 \chi^2}{2 C[\phi(\psi + \chi)]} - V[\phi(\psi + \chi)]. \tag{12}$$

The form of ϕ as a function of ψ and χ is determined by the conditions (10) and (11), except constants. However, there are some constraints on $A(\phi)$ and $C(\phi)$. As indicated in (6), (10) and (11), $A(\phi)$ and $C(\phi)$ should not be zero in the configuration space. Once the functions $A(\phi)$, $C(\phi)$ and $V(\phi)$ and the initial conditions are determined, the evolution of the system in (5) is fixed. Based on the discussions above, we can simplify the analysis on the single field model (5) by analyzing the two-field model (12).

3. A specific case with temporary phantom phase

We will study the evolving behaviors of such type of models for a simple case with $A(\phi) = -1$, $V(\phi) = 0$. Thus the Lagrangian is simplified as

$$\mathcal{L}' = -\frac{1}{2} \nabla_\mu \psi \nabla^\mu \psi + \frac{1}{2} \nabla_\mu \chi \nabla^\mu \chi - \frac{M_{\text{pl}}^2 \chi^2}{2 C[\phi(\psi + \chi)]}. \tag{13}$$

From Eqs. (10) and (11), one has the relation $\phi = -(\psi + \chi)$. The equations of motion for the two fields are:

$$\Box \psi + \frac{M_{\text{pl}}^2 C'(\psi + \chi)}{2 C^2(\psi + \chi)} \chi^2 = 0,$$
$$\Box \chi - \frac{M_{\text{pl}}^2 C'(\psi + \chi)}{2 C^2(\psi + \chi)} \chi^2 + \frac{M_{\text{pl}}^2}{C(\psi + \chi)} \chi = 0, \tag{14}$$

where the prime is the derivative with respect to $\psi + \chi$. In the Friedmann–Robertson–Walker universe, $\square = \partial^2/\partial t^2 + 3H\partial/\partial t$ with H being the Hubble expansion rate. Furthermore, one can easily get the density and the pressure of dark energy, which are:

$$\rho = -\frac{\dot{\psi}^2}{2} + \frac{\dot{\chi}^2}{2} + \frac{M_{\text{pl}}^2 \chi^2}{2C(\psi + \chi)}, \tag{15}$$

$$p = -\frac{\dot{\psi}^2}{2} + \frac{\dot{\chi}^2}{2} - \frac{M_{\text{pl}}^2 \chi^2}{2C(\psi + \chi)}, \tag{16}$$

and the equation of state is:

$$w = \frac{p}{\rho} = -1 - \frac{\dot{\psi}^2 - \dot{\chi}^2}{-\frac{\dot{\psi}^2}{2} + \frac{\dot{\chi}^2}{2} + \frac{M_{\text{pl}}^2 \chi^2}{2C(\psi + \chi)}}, \tag{17}$$

where the dot represents the derivative with respect to time. χ is quintessence-like and ψ is phantom-like. They couple to each other through the effective potential, i.e., the last term in the right-hand of equation (13):

$$V_{\text{eff}} = \frac{M_{\text{pl}}^2 \chi^2}{2C[\phi(\psi + \chi)]}. \tag{18}$$

The coupling function considered in this Letter is

$$C[\phi(\psi + \chi)] = C_0 \left[\frac{\pi}{2} + \arctan\left(\frac{-\lambda\phi}{M_{\text{pl}}} \right) \right]$$
$$= C_0 \left[\frac{\pi}{2} + \arctan\left(\frac{\lambda(\psi + \chi)}{M_{\text{pl}}} \right) \right], \tag{19}$$

thus

$$C'(\psi + \chi) = \frac{C_0 \lambda}{M_{\text{pl}}\left[1 + \frac{\lambda^2}{M_{\text{pl}}^2}(\psi + \chi)^2\right]}. \tag{20}$$

Because $C(\psi + \chi)$ is almost constant when $|\psi + \chi| \gg 0$, ψ and χ are nearly decoupled at these regimes. We call them as "weak coupling" regimes. By contrast, the two fields couple tightly in the "strong coupling" regime where $|\psi + \chi| \sim 0$. In the weak coupling regime, as shown in Eq. (14), the phantom-like field ψ behaves as a massless scalar field and its energy density $-(1/2)\dot{\psi}^2$ dilutes as a^{-6}, where a is the scale factor of the universe. The quintessence-like field χ has a mass term with $m_\chi = M_{\text{pl}}/\sqrt{C(\psi + \chi)}$. Its behavior is determined by the ratio of m_χ/H. If $m_\chi \ll H$, χ is slow-rolling and it behaves like a cosmological constant. On the other hand in cases $m_\chi \gg H$, the kinetic term and potential oscillate coherently and assembly evolve as a^{-3}, just like that of collisionless dust.

It is however more complicated in the strong coupling regime. If the effective potential V_{eff} is negligible in comparison with the energy density of the dominant component in the universe, as in the period of radiation and matter domination, the Hubble damping terms $3H\dot{\psi}$ and $3H\dot{\chi}$ dominates in the equations of motions, see Eq. (14), both ψ and χ are "frozen" and the equation of state of dark energy $w \simeq -1$. If V_{eff} contributes significantly to the energy density of the universe when dark energy is in the strong coupling regime, both of the fields will relax to their equilibrium points with large
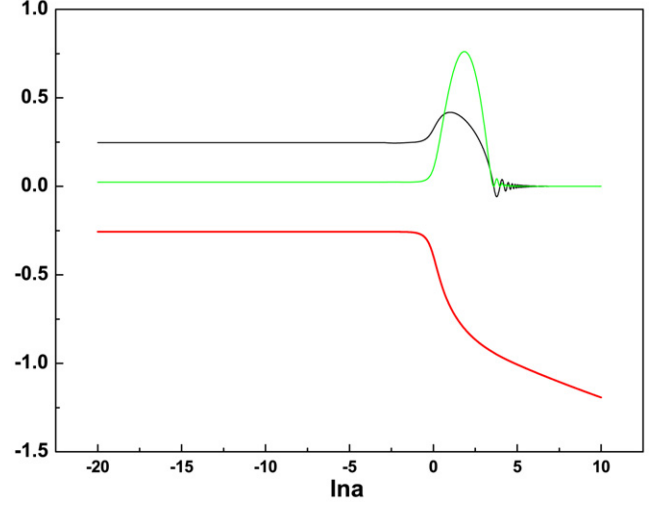

Fig. 1. The effective potential $V_{\text{eff}} \times C_0$ (the green line), χ (the black line), and ψ (the red line in the web version) as functions of $\ln a$ for $C_0/M_{\text{pl}}^2 = 6.0 \times 10^{121} M_{\text{pl}}^{-2}$, $\lambda = 25$, and the initial values are $\psi_i = -0.26 M_{\text{pl}}$, $\dot{\psi}_i = 3.52 \times 10^{-62} M_{\text{pl}}^2$, $\chi_i = 0.25 M_{\text{pl}}$, $\dot{\chi}_i = -3.62 \times 10^{-62} M_{\text{pl}}^2$, with $\Omega_{DE_0} \approx 0.73$.

velocities. Because $C(\psi + \chi)$ and $C'(\psi + \chi)$ are positive, the acceleration of ψ, $\frac{M_{\text{pl}}^2 C'(\psi + \chi)}{2C^2(\psi + \chi)} \chi^2$ is larger than that of χ: $\frac{M_{\text{pl}}^2 C'(\psi + \chi)}{2C^2(\psi + \chi)} \chi^2 - \frac{M_{\text{pl}}^2}{C(\psi + \chi)} \chi$, provided χ is positive. Hence, the ratio of $\dot{\psi}^2/\dot{\chi}^2$ will increase and from Eq. (17) the equation of state w will become less than -1 when $\dot{\psi}^2 > \dot{\chi}^2$. Otherwise, if χ is negative, $\dot{\psi}^2/\dot{\chi}^2$ will decrease with the expansion of the universe.

It is necessary to address more about the equilibrium points of ψ and χ. Through simple algebraic calculations of $\partial V_{\text{eff}}/\partial \psi = 0$ and $\partial V_{\text{eff}}/\partial \chi = 0$, we find the equilibrium point of ψ is in infinity except for the line of $\chi = 0$. In the χ direction, the zero point $\chi = 0$ is the unique minimum. So, if the initial condition is chosen as χ is not close to zero, the phantom-like field ψ will roll up the potential monotonically, this is along the direction of $\psi \to -\infty$ and to reduce $C(\psi + \phi)$. The quintessence-like field χ will relax down to the zero point. In a word, the system will evolve to the weak coupling regime and the field χ will get a large mass $m_\chi = M_{\text{pl}}/\sqrt{C(\psi + \chi)}$ because $C(\psi + \chi) \to 0$ as $\psi + \chi \to -\infty$. In Fig. 1, the effective potential (the green line), χ (the black line), and ψ (the red line) as functions of $\ln a$ are plotted.

We plot the EOS of such a dark energy model in Fig. 2 and Fig. 3 with different initial values. We choose such initial conditions that the dark energy starts in the strong coupling regime and $\chi > 0$ at high red-shift. We can see that the dark energy is frozen quickly at the initial time. Then it becomes significant around the redshift of $z \sim 1$, and the phantom kinetic term $\dot{\psi}^2$ becomes larger than the quintessence kinetic term $\dot{\chi}^2$. The dark energy crosses the boundary of cosmological constant and its equation of state becomes less than -1. In the future, the system will evolve to the weak coupling regime, $\dot{\psi}^2$ will dilute quickly and χ will get a large mass. The whole system will behave as cold matter and its equation of state will oscillate
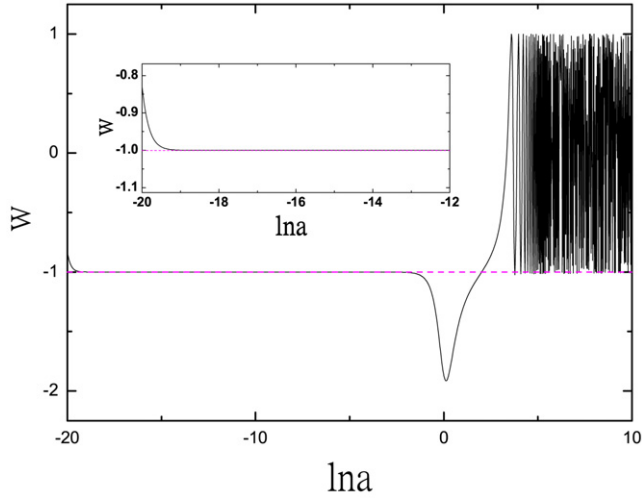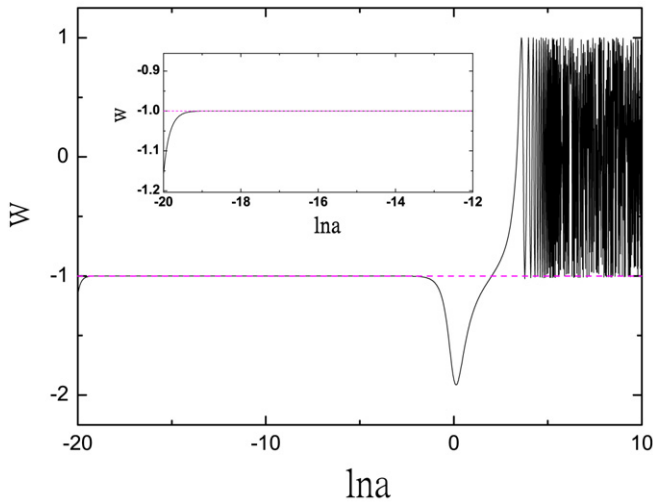
Fig. 2. The equation of state w as a function of $\ln a$ for $C/M_{\rm pl}^2 = 6.0 \times 10^{121} M_{\rm pl}^{-2}$, $\lambda = 25$, and the initial values are $\psi_i = -0.26 M_{\rm pl}$, $\dot{\psi}_i = 3.52 \times 10^{-62} M_{\rm pl}^2$, $\chi_i = 0.25 M_{\rm pl}$, $\dot{\chi}_i = -3.62 \times 10^{-62} M_{\rm pl}^2$, with $\Omega_{DE_0} \approx 0.73$.

Fig. 3. The equation of state w as a function of $\ln a$ for $C/M_{\rm pl}^2 = 6.0 \times 10^{121} M_{\rm pl}^{-2}$, $\lambda = 25$, and the initial values are $\psi_i = -0.26 M_{\rm pl}$, $\dot{\psi}_i = -2.84 \times 10^{-62} M_{\rm pl}^2$, $\chi_i = 0.25 M_{\rm pl}$, $\dot{\chi}_i = 2.74 \times 10^{-62} M_{\rm pl}^2$, with $\Omega_{DE_0} \approx 0.73$.

around the point of $w = 0$. So, the universe will exit from the phantom phase and end in the state of matter-domination. This is consistent with the analysis above. Our result resembles the late time behavior of "B-inflation" model [52].

The cosmological meanings of such a model are as follows:

- In this model, we give a kind of cosmological scenario which differs from the former quintom dark energy models. This model can give twice crossing of w, and can give a nice exit of phantom which stays just for a period of time, avoiding "big-rip" to happen.
- This kind of w gives an example of feature EOS in model building in field theory, which is being paid more and more attention on by current data-fitting [53].

- At late time, w oscillates high frequency around zero, the universe will end accelerated expanding at some time.

4. Summary

In summary, we pointed out that for quintom model of single scalar field with higher derivative, the EOS w can have some interesting behaviors. We provide a scenario where the EOS w starts from above -1, transits to below -1, then comes back to above -1. This in some sense implies that $w < -1$ may happen just for a period of time. With this behavior of w, this scenario might be able to get rid of the problem caused by phantom. For phantom theory, the EOS w is always less than -1, and there might be many problems such as ending in "big-rip" as well as other singularities, and quantum instability. However in some class scenario of quintom with higher derivative, the evolution of $w < -1$ is very much like the "tachyon" existing only during the phase transition [54]. Thus the "big-rip" problem [46] is solved in such a context.

The quantum instability of phantom universe is discussed in detail in Refs. [55,56]. Our quintom model based on higher derivative theory also has ghost degree and the problem of quantum instability. However, as pointed out in Ref. [57], the problem of quantum instability arises because ϕ and $\Box\phi$ are quantized in canonical way independently. In fact, both of them are determined by ϕ, and a more appropriate quantization method seems to be possible to avoid the instability.

This work not only provides some new examples for the list of field theory model of dark energy, which deserves being included in a more thorough classification, but useful for stimulating the studies on the field theory with higher derivatives.

Acknowledgements

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