SO(1, 1) dark energy model and the universe transition *

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March 24, 2022

Abstract

We suggest the SO(1, 1) scalar field model of dark energy. In this model, the Lagrangian may be decomposed as that of the real quintessence model and the negative coupling energy term of $\Phi$ to $a$. The existence of the coupling term $L_c$ leads to a wider range of $w_\Phi$ and overcomes the problem of negative kinetic energy in the phantom universe model. We propose a power-law expansion kinetics model of universe with time-dependent power, which can describe the universe transition from ordinary acceleration to super acceleration. We give also a simple discussion of Big Rip singularity, and point out the possibility that the universe driven by phantom avoid it.

PACS number(s) 98.80.Cq, 98.80.Hm

I Introduction

The observation of type Ia supernovae (SNe Ia) \cite{1} and the cosmic microwave background power spectrum \cite{2} suggest that our universe is undergoing accelerated expansion and spatially flat, which have led to the consensus that in the current universe consists of roughly 73\% dark energy and 27\% matter. Probing the nature of the dark energy is one of the major fundamental challenges in astronomy and physics today. In order to explain the nature of dark energy, many models have been proposed, such as, quintessence \cite{3}, k-essence \cite{4},

*ITP PHD Project 22B580; Liaoning Province Educational Committee Research Project; National Nature Science Foundation Project of China.
tachyon, phantom, Chaplygin gas, spintessence, etc. So far, the theoretical probe of dark energy focuses mainly on the evolution of the dark energy density or the equation of state. The current astronomical observations data can not determine completely the nature of dark energy. The analysis based on the SNe Ia data seems to favor the existence of a phantom energy in the present universe. The phantom energy with negative kinetic energy (KE) violates the null dominated energy condition dynamically, the instability of the vacuum leads to the vacuum decay. According to the lifetime of the phantom particle can exceeds cosmological time scale if the momentum cutoff is smaller than $10^{-3} \text{eV}$. However, it is a pity that there is no such energy scale in particle physics. Thus, the problem of the instability of the vacuum is still an enigma, even will be puzzle in a long time.

Another open question is in what domain the dark energy equation of state ($w = \frac{p}{\rho}$) lies. The SNIa data with the constraints from WMAP observations rules out any rapid change in w in recent epochs and are completely consistent with the cosmological constant as the source of dark energy. However, combining the SNIa data with flat-universe constraints including the cosmic microwave background and large-scale structure, one can find $w = 1.02^{+0.13}_{-0.19}$ (and $w < -0.76$ at the 95% confidence level) for an assumed static equation of state of dark energy. Clearly, it is very difficult to obtain the severe constrain on w from the current observations. This is one of the main reasons why there are the various models of dark energy. The models of dark energy may approximately be classified into the following three possible categories: $w > -1$, $w = 1$ (cosmological constant) and $w < -1$ (phantom). Besides, one can imagine that dark energy might have changed from the past $w > -1$ to $w < -1$, since no result from the cosmological observational data doesn’t exclude this possible situation. Providing that the above case, then such models that allow for an arbitrarily w will be needed.

Boyle, Caldwell and Kamionkowski proposed the spintessence model for dark energy and
dark matter [11], which has a $U(1)$ symmetry and generalizes the quintessence model. From the Lagrangian $L = \frac{1}{2}(\dot{\phi}^2) - V(|\phi|)$ with $\phi = \phi_1 + i\phi_2$, $\phi^* = \phi_1 - i\phi_2$ and $|\phi| = \sqrt{\phi\phi^*}$, one can have the equivalent form with a $SO(2)$ symmetry, $L = \frac{1}{2}(\dot{\phi}_1^2 + \dot{\phi}_2^2) - V(|\phi|)$. Compared to the quintessence model with a real field, the spininessence model make an important improvement due to the $U(1)$ symmetry. In this paper, we propose the $SO(1,1)$ model of dark energy, in which the Lagrangian density may be decomposed as $L = L^Q_\Phi + L^c$, with $L^Q_\Phi$ that of quintessence and $L^c$ the coupling Lagrangian density of $\Phi$ to $a$. The model shows some new features, it can’t only describe the phantom universe but also the universe transition from ordinary acceleration to super acceleration phase, in principle. The paper is organized as follows. In Sec. II, we show the $SO(1,1)$ model and discuss the two special cases, one is the case that KE is much larger than the absolute of coupling energy (CE), and another can describe the variation of $w$ through $w = -1$. We suggest also the power-law expansion scale factor with time-dependent power, which has an advantage for illustrating the second case. In Sec. III, we discuss simply the problem of Big Rip, and give a brief summary of the $SO(1,1)$ model.

II $SO(2; \eta)$ model of dark energy

Based the spininessence model [11] and the extended complex model for dark energy [17], we propose the following dark energy model, the Lagrangian density of which is given by

$$L = \frac{1}{2}(\dot{\phi}_1^2 - \eta\dot{\phi}_2^2) - V(\sqrt{\phi_1^2 - \eta\phi_2^2}),$$

where $\phi_1$, $\phi_2$ are spatially homogeneous scalar fields, $\eta$ is a real parameter and $V$ is the potential. The Lagrangian (1) possesses clearly certain symmetry. By writing

$$L = \frac{1}{2}\Psi^T\eta\Psi - V(\sqrt{\Psi^T\eta\Psi}),$$

$$\Psi^T_\eta = \Psi^T M(\eta), \quad \Psi^T = (\phi_1, \phi_2)^T, \quad M(\eta) = \text{diag}(1, \eta),$$

where $\Psi^T_\eta$ is the conjugate transpose of $\eta$ multiplied by $\Psi^T$.
where "T" denotes the transpose of matrix, then one can see that under the transformation

$$\Psi' = M \Psi, \quad M = \begin{pmatrix} c(\alpha; \eta) & s(\alpha; \eta) \\ s(\alpha; \eta) & -\eta c(\alpha; \eta) \end{pmatrix}, \quad c^2(\alpha; \eta) - \eta s^2(\alpha; \eta) = 1,$$

(4)

where $\alpha$ is a real "angular" parameter, $c(\alpha; \eta) = \sum_{n=0}^{\infty} \frac{\eta^n}{(2n)!} \alpha^{2n}$ and $s(\alpha; \eta) = \sum_{n=0}^{\infty} \frac{\eta^n}{(2n+1)!} \alpha^{2n+1}$.

[18], the Lagrangian (4) holds invariant. We call this symmetry the $SO(2; \eta)$ symmetry, which includes the $SO(2)$ and $SO(1, 1)$ symmetries.

Defining the new field variables $\Phi$ and $\theta$ by $\Phi = \sqrt{\phi_1^2 - \eta \phi_2^2}$ and $\tan(\theta; \eta) = \frac{s(\theta; \eta)}{c(\theta; \eta)} = \frac{\phi_1}{\phi_2}$, then from (1) we have

$$L_\Phi = \frac{1}{2}(\dot{\Phi}^2 - \eta \Phi^2 \dot{\theta}^2) - V(\Phi).$$

(5)

For $\eta = -1$, (1) yields the Lagrangian density [11, 21] (see also Refs. [22]). For a spatially flat, isotropic and homogeneous universe consisting of the dust-like matter and the dark energy originating from the $SO(2; \eta)$ scalar fields, we have the Friedman equations

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}(\rho_m + \rho_\Phi),$$

(6)

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho_m + \rho_\Phi + 3p_\Phi),$$

(7)

and the motion equations of fields

$$\ddot{\Phi} + 3H \dot{\Phi} + \eta \dot{\theta}^2 \Phi + V'(\Phi) = 0,$$

(8)

$$\dot{\theta} + (2\frac{\dot{\Phi}}{\Phi} + 3H) \dot{\theta} = 0,$$

(9)

with

$$\rho_\Phi = \frac{1}{2}(\dot{\Phi}^2 - \eta \Phi^2 \dot{\theta}^2) + V(\Phi),$$

(10)

$$p_\Phi = \frac{1}{2}(\dot{\Phi}^2 - \eta \Phi^2 \dot{\theta}^2) - V(\Phi),$$

(11)
where $H = \frac{\dot{a}}{a}$ is the Hubble parameter, a dot and a prime denote derivatives with respect to $t$ and $\Phi$, respectively. Equation (10) is independent of the parameter $\eta$, and the solution is

$$\dot{\theta} = \frac{c}{a^3 \Phi^2},$$

where $c$ is a constant.

Decomposing the Lagrangian density (5) into $L_\Phi^Q$ and $L_c$

$$L_\Phi = L_\Phi^Q + L_c, \quad L_\Phi^Q = \frac{1}{2} \dot{\Phi}^2 - V(\Phi), \quad L_c = -\frac{1}{2} \eta c^2 a^{-6} \Phi^{-2},$$

then (11) and (12) may be reformulated to

$$\rho_\Phi = \rho_\Phi^Q + \rho_\Phi^c, \quad \rho_\Phi^Q = \frac{1}{2} \dot{\Phi}^2 + V(\Phi), \quad \rho_\Phi^c = -\frac{1}{2} \eta \Phi^2 \dot{\theta}^2$$

$$p_\Phi = p_\Phi^Q + p_\Phi^c, \quad p_\Phi^Q = \frac{1}{2} \dot{\Phi}^2 - V(\Phi), \quad p_\Phi^c = -\frac{1}{2} \eta \Phi^2 \dot{\theta}^2,$$

where $\rho_\Phi^Q$ and $p_\Phi^Q$ are the contributions to the total energy density and pressure from $L_c$.

Defining $w_c = \frac{p_c}{\rho_c}$, then there is $w_c = 1$, which is independent of $\eta$. In the $SO(1, 1)$ model, i.e., the case of $\eta = 1$, the equation of state is given by

$$w = \frac{\dot{\Phi}^2 - V(\Phi) + \rho_\Phi^c}{\dot{\Phi}^2 + V(\Phi) + \rho_\Phi^c},$$

which shows clearly some new features: the existence of the negative CE, which leads to the wide range of $w$ and the possible $w < -1$ even though the KE holds always nonnegative. Provided that $KE \geq |CE|$, then $w_\phi \geq -1$; if $KE < |CE|$, then $w_\phi < -1$; when $KE + CE$ changes from a positive to a negative value, $w_\phi$ changes from $>-1$ to $< -1$. Thus, the $SO(1, 1)$ model of dark energy may allow for an arbitrary value of $w$, in principle.

In the following, we will focus on the second and third cases. First, let us discuss the phantom case, i.e., $w < -1$. Assuming that the equations of state of matter and dark energy, $w_m$ and $w_\phi$, and the fractions of matter and dark energy, $\Omega_m$ and $\Omega_\phi$, satisfying $\Omega_m + \Omega_\phi \simeq 1$, are varying slowly, then from equations (6) and (7) one can obtain

$$a \simeq (\alpha + \beta t)^{2/3(1+\Omega_m w_m + \Omega_\phi w_\phi)}$$

with $\alpha$ and $\beta$ two constants and $w_\phi < -\frac{1+3\Omega_m w_m}{3\Omega_\phi}$. Defining
\[ \Sigma = \Omega_m a_m + \Omega_\Phi a_\Phi \] and letting \( \alpha = -a_m \Sigma \) and \( \beta = a_m (1 + \Sigma) / t_m \) with \( t_m \) a constant time and \( a_m = a(t_m) \), then we have

\[ a = a_m [ -\Sigma + (1 + \Sigma) \left( \frac{t}{t_m} \right)^{2/3(1 + \Sigma)} ], \quad (16) \]

\[ H = \frac{\dot{a}}{a} = \frac{2}{3[-\Sigma t_m + (1 + \Sigma) t]}, \quad \dot{H} = \frac{-2(1 + \Sigma)}{3[-\Sigma t_m + (1 + \Sigma) t]^2}. \quad (17) \]

Considering the matter component as the pressureless fluid, i.e., \( p_m = 0 \), then it evolves according to

\[ \rho_m = \rho_{m0} (a_0 / a)^3, \quad \rho_{m0} = \rho_m (t = t_0) \] with \( t_0 \) the age of the universe. In this case, noting that \( \ddot{a} = H^2 + \dot{H} \), from equations (16), (17), (12) and (17) we obtain

\[ \frac{1}{2} \dot{\Phi}^2 - \frac{1}{2} c^2 \Phi^{-2} a^{-6} = -\frac{1}{2} \rho_m + \frac{1 + \Sigma}{12 \pi G [-\Sigma t_m + (1 + \Sigma) t]^2}, \quad (18) \]

\[ V = -\frac{1}{2} \rho_m + \frac{1 - \Sigma}{12 \pi G [-\Sigma t_m + (1 + \Sigma) t]^2}. \quad (19) \]

For equation (18), let us consider such a special case that \( KE \ll |CE| \). Letting \( M = \rho_m a^3 \) and \( N = -\frac{1 + \Sigma}{6 \pi G t_m} a^6_m \), then from equation (18) we obtain

\[ \Phi \simeq c [Ma^3 + N(a/a_m)^6]^{3(1 + \Sigma)} \]

(20)

For late time evolution, there are \( \Omega_\Phi \to 1, \Sigma \sim w_\Phi \), and equation (20) reduces to

\[ \Phi \simeq c N^{-\frac{1}{2}} (a/a_m)^{\frac{3}{2} \gamma_\Phi - 3}. \quad (21) \]

Defining \( \gamma_\Phi = 1 + w_\Phi \) and \( \rho_c = -c^2 \Phi^{-2} a^{-6} \), then there is approximately

\[ \rho_c \simeq -\frac{2 M_P^2 \gamma_\Phi}{3 t_m^2} (a/a_m)^{-3 \gamma_\Phi}, \quad (22) \]

where \( M_P = 1/\sqrt{8 \pi G} \) is the reduced Planck energy. Defining \( \rho_k = \frac{1}{2} \dot{\Phi}^2 \), then from equation (21) we obtain

\[ \rho_k = \frac{3 c^2 (\gamma_\Phi - 2)^2}{8 \gamma_\Phi M_P^2} a^{-6}. \quad (23) \]
From equations (22) and (23), one see that the condition \( \rho_k \ll |\rho| \) may be guaranteed if
\[
a \gg \left[ \frac{3c(\gamma_\Phi-2)t_m}{4\gamma_\Phi M_p^2} \right]^2 a_m^{-\frac{3\gamma_\Phi}{\gamma_\Phi-1}}
\] is satisfied.

In what follows, we discuss the possible evolution of dark energy from \( w > -1 \) to \( w < -1 \).

In order to accomplish this purpose, we assume the following scale factor
\[
a \sim t^n,
\] (24)
with \( n \) a time-dependent power. From (24), one has the Hubble parameter and its first derivative with respect to time
\[
H = \dot{n} \ln t + \frac{n}{t}, \quad \dot{H} = \ddot{n} \ln t + 2 \frac{\dot{n}}{t} - \frac{n}{t^2},
\] (25)
where a dot denotes the derivative with respect to time. Assuming that \( n \) has the form
\[
n = n_0 + bt,
\] (26)
where \( n_0 \) and \( b \) are two constants, then from equation (25) we obtain
\[
H = b(\ln t + 1) + n_0 t^{-1},
\] (27)
\[
\dot{H} = bt^{-1} - n_0 t^{-2}.
\] (28)

Equation (28) implies a critical time \( t_c = \frac{n_0}{b} > 0 \) when the transition from ordinary acceleration (\( \dot{H} < 0 \)) to super acceleration expansion phase (\( \dot{H} > 0 \)) occurs (we call this transition the super expansion transition, compared to the transition from decelerated to accelerated expansion). Considering the matter component as the pressureless fluid, then from equations (21), (27), (10), (11), (27) and (28), we obtain
\[
\dot{\Phi}^2 + 2L_\Phi^c = -\rho_m 0 t_0^3(n_0 + bt) + 2\rho_0 n_0 - bt) 3H_0^2 t^2, \quad L_\Phi^c = -\frac{1}{2}c^2 \Phi^2 t^{-6}(n_0 + bt),
\] (29)
\[
2V = -\rho_m 0 t_0^3(n_0 + bt) + 2\rho_0 n_0 - bt) + 2\rho_0 bt(\ln t + 1) + n_0^2) 3H_0^2 t^2 + 2\rho_0 bt(\ln t + 1) + n_0^2) 3H_0^2 t^2,
\] (30)
where $\rho_0$ and $H_0$ are the total energy density and Hubble parameter of the current universe. For the case of both $b$ and $n_0$ being positive, the term $-\rho_0 t^{3(n_0 + bt)}$ will fall faster and faster than $2\rho_0 t^{3(n_0 - bt)}$ as $t$ increases, thus for $t \gg 1$ equations (29) and (30) will reduce to

$$
\dot{\Phi}^2 - c^2 \dot{\Phi} = \frac{2\rho_0 (n_0 - bt)}{3H_0^2 t^2},
$$

(31)

$$
2V = \frac{2\rho_0 (bt - n_0)}{3H_0^2 t^2} + \frac{2\rho_0 [bt(\ln t + 1) + n_0]^2}{H_0^2 t^2}.
$$

(32)

In an enough small neighborhood of $t_c$, there is $bt_c - n_0 \simeq 0$ and thus equations (31) and (32) reduce further to

$$
\Phi^2 \simeq 2c \int t^{-3(n_0 + bt)} dt,
\quad V \simeq \frac{\rho_0 [bt(\ln t + 1) + n_0]^2}{H_0^2 t^2}.
$$

(33)

Assuming a small $b$, then $bt$ is a slowly changing function of $t$ and we can approximately have $\Phi^2 \simeq \frac{2c}{1 - 3(n_0 + bt)} t^{-3(n_0 + bt)+1}$.

In the $SO(1,1)$ model, the kinetic part $\frac{1}{2} \dot{\Phi}^2$ is extended to $K_{eff} = \frac{1}{2} \dot{\Phi}^2 + \rho_\Phi$. The slow-rolling in quintessence and slow-climbing conditions in phantom model are replaced by $|K_{eff}| \ll V$, here. In this case, the evolution of dark energy (or phantom energy) will depend mainly on the evolution of potential. Thus, the discussions on the evolution properties of quintessence or phantom should be valid for the current $SO(1,1)$ model.

### III Discussions

In the previous section we propose the $SO(1,1)$ model of dark energy and have considered the two special cases. This section will devoted to a simple discussion on Big Rip singularity and the instability of the model and give a summary of the $SO(1,1)$ model.

For a phantom universe described by the power-law scale factor $a = a_m[-w_\Phi + (1 + w_\Phi) (\frac{t}{t_m})^{2/3(1+w_\Phi)}]$ with $w_\Phi < -1$ a constant, one can almost be sure to infer the occurrence of Big Rip [6,7]. However, provided that $w_\Phi$ evolves according to $w_\Phi = -1 + O(t^{-n})$ with $n > 1$,
then the universe may avoid the Big Rip and will stay on the approximate de Sitter phase forever. So, the phantom energy doesn’t always lead to a Big Rip of universe. From equations (29) and (30) (or (31) and (32)), one can have $w_\Phi = \frac{\dot{\Phi}^2 + 2\mathcal{L}_c}{\Phi^2 + 2\mathcal{L}_c} \approx -1 - \frac{2(\beta t^{-1} - n_0 t^{-2})}{3(\ln t + 1) + n_0 t} \approx -1 - \frac{2}{3(\ln t + 1)} + O(t^{-2}[\ln t]^{-1})$ for $t \gg t_c$. This is an example that the universe is driven by phantom but evades a Big Rip singularity.

In the $SO(1,1)$ model dark energy falls into the two ranges, $w_\Phi > -1$ and $w_\Phi < -1$ corresponding to $KE + CE > 0$ and $KE + CE < 0$, respectively. Clearly, in the latter case the model violates the weak energy condition, $\rho_\Phi + p_\Phi < 0$, and thus in this case dark energy has an instable property, like the all other phantom models. As has been seen in Sec. II, this instability may lead to a Big Rip singularity, the approximate de Sitter phase or the other cases, which depend on the behaviors of dark energy.

From equations (13)-(15), one can see the scalar model for dark energy with $SO(1,1)$ symmetry contains the scalar quintessence model, the appearance of the coupling Lagrangian density $\mathcal{L}_c$ is the result of the $SO(1,1)$ symmetry. In this model, the KE term holds always nonnegative for either $w > -1$ or $w < -1$. The negative CE term plays a fundamental role, and decreases generically with the growth of $a$ and approaches zero when $a \to \infty$. For example, it is proportional to $a^{-6}$ for a constant $\Phi$. To sum up, our dark energy model has the following features, the wide range of the equation of state $w$, the nonnegative KE and the existence of the CE term or the $SO(1,1)$ symmetry.

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