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Evolution of spherical over-densities in tachyon scalar field model

M.R. Setare [a], F. Felegary [b], F. Darabi [b,*]

[a] Department of Science, Campus of Bijar, University of Kurdistan, Bijar, Iran
[b] Department of Physics, Azarbaijan Shahid Madani University, Tabriz, 53714-161, Iran

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ABSTRACT

We study the tachyon scalar field model in flat FRW cosmology with the particular potential ϕ^{-2} and the scale factor behavior $a(t) = t^n$. We consider the spherical collapse model and investigate the effects of the tachyon scalar field on the structure formation in flat FRW universe. We calculate $\delta_c(z_c)$, $\lambda(z_c)$, $\xi(z_c)$, $\Delta_V(z_c)$, $\log[\nu f(\nu)]$ and $\log[n(k)]$ for the tachyon scalar field model and compare the results with the results of EdS model and ΛCDM model. It is shown that in the tachyon scalar field model the structure formation may occur earlier, in comparison to the other models.

1. Introduction

The last cosmological and astrophysical data of Large Scale structure, the observations of type Ia and Cosmic Microwave Background radiation have demonstrated that currently there is an acceleration expansion phase in the universe [4,18]. The cosmic expansion can be well described by a negative pressure so-called dark energy (DE). The simplest candidate for DE is the cosmological constant. However, the cosmological constant suffers from the fine-tuning and the cosmic coincidence problems [6,24]. Therefore, to avoid these problems, different models for dark energy have been proposed such as quintessence, K-essence, tachyon [20], ghost [27], phantom, quintom [5], and the quantum gravity models, as well as holographic [28] and new agegraphic models [6,14]. The tachyon model as a scalar field model arises in particle physics and string theory. Thus, it can be considered as one of the potential candidates to describe the nature of the DE.

On the other hand, the problem of structure formation in the universe is a very important issue in theoretical cosmology. A simple model of structure formation is the spherical collapse model. The spherical collapse model was presented by Gunn and Gott [8]. This model studies the evolution of growth of overdense structures with respect to the dynamics of scale factor or cosmic redshift. The dynamics of overdense structures depends on the dynamics of the background Hubble flow and expansion of the universe. In the frame of general relativity, the spherical collapse model has been studied [7,9,19]. In this paper, we study the spherical collapse and the evolution of spherical overdensities in the framework of tachyon scalar field model and compare the results with the results of Einstein-de Sitter (EdS) and Λ-Cold Dark Matter (ΛCDM) models.

2. Cosmology with Tachyon scalar field

The Lagrangian of tachyon scalar field over a cosmological background is given by [26]

$$\mathcal{L} = -V(\phi)\sqrt{1-\partial_a\phi\,\partial^a\phi}, \tag{1}$$

where ϕ and $V(\phi)$ are the tachyon scalar field and tachyon potential, respectively, and we consider the Friedmann–Robertson–Walker (FRW) metric having the cosmic time t dependent scale factor $a(t)$. For a homogeneous field, the equation of motion is obtained as

$$\frac{\ddot{\phi}}{1-\dot{\phi}^2} + 3H\dot{\phi} + \frac{\acute{V}(\phi)}{V(\phi)} = 0, \tag{2}$$

where the symbols $\cdot$ and $'$ denote the derivatives with respect to t and ϕ, respectively, and $H = \dot{a}/a$ is called the Hubble parameter. In the flat FRW universe, the energy density ρ_Λ and the pressure p_Λ of the tachyon field read as

$$\rho_\Lambda = \frac{V(\phi)}{\sqrt{1-\dot{\phi}^2}}, \tag{3}$$

$$p_\Lambda = -V(\phi)\sqrt{1-\dot{\phi}^2}. \tag{4}$$

For the pressureless matter and tachyon scalar field matter, the Friedmann equation is given by

* Corresponding author.
E-mail addresses: rezakord@ipm.ir (M.R. Setare), falegari@azaruniv.ac.ir (F. Felegary), f.darabi@azaruniv.ac.ir (F. Darabi).

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$$H^2 = \frac{1}{3M_{pl}^2}(\rho_m + \rho_\Lambda), \tag{5}$$

where ρ_Λ is the energy density of tachyon scalar field, and ρ_m is the density of pressureless matter. We suppose that there is no interaction between ρ_Λ and ρ_m, so the continuity equations are given separately by

$$\dot{\rho}_\Lambda + 3H\rho_\Lambda(1+\omega_\Lambda) = 0, \tag{6}$$

$$\dot{\rho}_m + 3H\rho_m = 0. \tag{7}$$

Using Eqs. (3) and (4) and also $p_\Lambda = \omega_\Lambda \rho_\Lambda$, the equation of state parameter (EoS) for tachyon scalar field is obtained as

$$\omega_\Lambda = \dot{\phi}^2 - 1. \tag{8}$$

The requirement for a real ρ_Λ results in $0 < \dot{\phi}^2 < 1$ according to which ω_Λ should vary as $-1 < \omega_\Lambda < 0$. The fractional energy densities are defined by

$$\Omega_\Lambda = \frac{\rho_\Lambda}{3M_{pl}^2 H^2}, \tag{9}$$

$$\Omega_m = \frac{\rho_m}{3M_{pl}^2 H^2}. \tag{10}$$

Taking time derivative of Eq. (9) and using Eq. (6) yields

$$\dot{\Omega}_\Lambda = -\Omega_\Lambda H\Big[3(1+\omega_\Lambda) + 2\frac{\dot{H}}{H^2}\Big]. \tag{11}$$

Also, taking time derivative of Eq. (5) and using Eqs. (6) and (7) yields

$$2\frac{\dot{H}}{H^2} = -3(1+\omega_\Lambda\Omega_\Lambda). \tag{12}$$

Using Eq. (12) and inserting Eq. (11), we obtain

$$\Omega'_\Lambda = 3\omega_\Lambda\Omega_\Lambda(\Omega_\Lambda - 1). \tag{13}$$

Here, the prime is the derivative with respect to $x = \ln a$ where $a = (1+z)^{-1}$ and z is the cosmic redshift. Using $\frac{d}{dx} = -(1+z)\frac{d}{dz}$ and Eq. (8), one finds

$$\frac{d\Omega_\Lambda}{dz} = -3\Omega_\Lambda(\Omega_\Lambda - 1)(\dot{\phi}^2 - 1)(1+z)^{-1}. \tag{14}$$

The differential equation for the evolution of dimensionless Hubble parameter, $E(z) = \frac{H}{H_0}$, in tachyon scalar field model, is obtained by using Eqs. (6), (7), (8) and (12) as follows

$$\frac{dE}{dz} = \frac{3}{2}\frac{E}{(1+z)}\Big[1 + \Omega_\Lambda(\dot{\phi}^2 - 1)\Big]. \tag{15}$$

Now, we consider the following particular potential which results in the scalar field with linear time dependence and the scale factor with suitable power law behavior, as follows [26]

$$V(\phi) = \frac{2n}{M_{pl}^2}(1 - \frac{2}{3n})^{\frac{1}{2}}\frac{1}{\phi^2}, \tag{16}$$

$$\phi = \sqrt{\frac{2}{3n}}t, \tag{17}$$

$$a(t) = t^n. \tag{18}$$

Taking time derivative of Eq. (17), inserting in Eq. (8) and using Eq. (18), we can obtain the equation of state parameter for tachyon scalar field model

$$\omega_\Lambda = \frac{2}{3n} - 1. \tag{19}$$

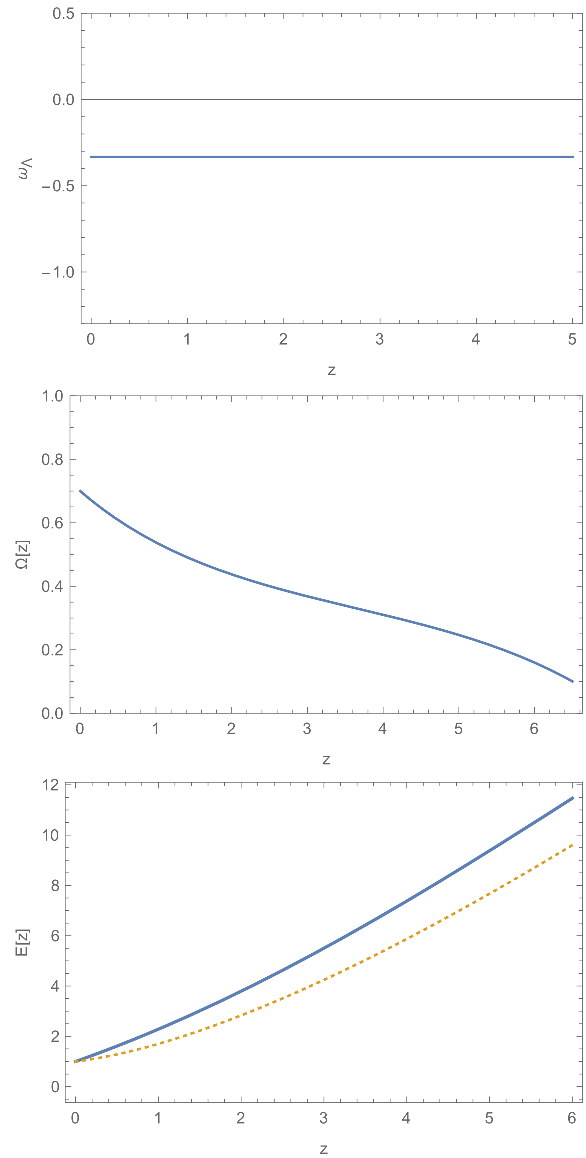

Fig. 1. The evolution of EoS parameter (top), dark energy density parameter (middle), and dimensionless Hubble parameter (down) of tachyon scalar field model with respect to the redshift parameter z. The thick line represents the tachyon scalar field model for $n = 1$ and the dotted line shows the ΛCDM model.

In Eq. (19), we can see that if $n \geq \frac{2}{3}$, then we will have $-1 < \omega_\Lambda < 0$. Using Eq. (19) and inserting it in Eqs. (14), (15) we can get the evolution of EoS parameter (ω_Λ), the density parameter of dark energy (Ω_Λ), and the dimensionless Hubble parameter ($E(z)$) in tachyon scalar field model as a function of cosmic redshift. In Fig. 1, assuming the present values $\Omega_{\Lambda_0} \approx 0.7$, $\Omega_{m_0} \approx 0.3$ and $H_0 \approx 67.8\frac{\text{km}}{\text{s Mpc}}$, we have shown the evolution of EoS parameter, the evolution of density parameter and the evolution of dimensionless Hubble parameter of tachyon scalar field model with respect to the redshift parameter z for the typical value $n = 1$.

3. Linear perturbation theory

In this section, we study the linear growth of perturbation of nonrelativistic dust matter by computing the evolution of growth factor $g(a)$ in tachyon scalar field model, and then compare it with the evolution of growth factor in EdS and ΛCDM models. The dif-