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Phenomenological Fluids from Interacting Tachyonic Scalar Fields

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Abstract In this paper we are interested to consider mathematical ways to obtain different phenomenological fluids from two-component Tachyonic scalar fields. We consider interaction between components and investigate problem numerically. Statefinder diagnostics and validity of the generalized second law of thermodynamics performed and checked. We suppose that our Universe bounded by Hubble horizon.

Keywords FRW cosmology · Dark energy · Phenomenology

1 Introduction

Modern cosmology faced with a problem when a set of observational data reveal the following picture of our Universe called modern era in theoretical cosmology. Observations of high redshift type SNIa supernovae [1–3] reveal the accelerating expansion of our Universe. Then, other series of observations like to investigation of surveys of clusters of galaxies show that the density of matter is very much less than critical density [4], observations of

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Cosmic Microwave Background (CMB) anisotropy indicate that the Universe is flat and the total energy density is very close to the critical $\Omega_{tot} \simeq 1$ [5]. Explanation of accelerated expansion of our Universe takes two different ways and now they are developing and evaluating as different approaches, however there is not any natural restriction of a possibilities of recombination of two approaches in one single approach. In that case we believe that joined approach will be more sufficient and rich with new and interesting physics. To explain recent observational data, which reveals accelerated expansion character of the Universe, several models were proposed. One of the possible scenarios (general relativity framework) is the existence of a dark energy with negative pressure and positive energy density giving an acceleration to the expansion [6, 7]. Now, astronomical studies and observational data of WMAP confirm that dark energy occupies about 73 % of the energy of our Universe. Other component, dark matter occupies about 23 %, and usual baryonic matter occupies about 4 %.

There are several models to describe dark energy such as the cosmological constant and its generalizations [8], or Chaplygin gas and its generalizations [9–17]. Also there are other candidates for the dark energy which are scalar-field dark energy models. A quintessence field [18] is a scalar field with standard kinetic term, which minimally coupled to gravity. In that case the action has a wrong sign kinetic term and the scalar field is called phantom [19]. Combination of the quintessence and the phantom is known as the quintom model [20]. Extension of kinetic term in Lagrangian yields to a more general frame work on field theoretic dark energy, which is called k-essense [21, 22]. A singular limit of k-essense is called Cuscuton model [23]. This model has an infinite propagating speed for linear perturbations, however causality is still valid. The most general form for a scalar field with second order equation of motion is the Galileon field which also could behaves as dark energy [24].

Among different viewpoints concerning to the nature of the dark component of the Universe, in this article, we accept that it could be described by a scalar field and we choose Tachyon as a scalar field. This paper is organized as follows. After introduction, in the next section, we consider two-component Tachyonic fluid and give motivation of our work. In Sect. 3 we write field equations include an interaction between components. Then check validity of the Generalized Second Law (GSL) of thermodynamics for this setting in Sect. 4. In Sect. 5 the statefinder diagnostics is performed as well. In Sect. 6 we give numerical analysis of the differential equations which obtained in previous sections. Finally in Sect. 7 we give conclusion and discuss about results.

2 Tachyonic Fluid

Tachyonic fluid described by the following relativistic Lagrangian [25],

$$L_{TF} = -V(\phi)\sqrt{1 - \partial_i\phi\partial^i\phi}. \tag{1}$$

Therefore, the stress energy tensor is given by,

$$T^{ij} = \frac{\partial L_{TF}}{\partial(\partial_i\phi)}\partial^j\phi - g^{ij}L_{TF}, \tag{2}$$

which yields to the following energy density and pressure,

$$\rho = \frac{V(\phi)}{\sqrt{1 - \partial_i\phi\partial^i\phi}}, \tag{3}$$

$$P = -V(\phi)\sqrt{1 - \partial_i\phi\partial^i\phi}, \tag{4}$$

respectively. Our next step is to present (3) and (4) as the following,

$$\begin{aligned}\rho &= \rho_1 + \rho_2,\\ P &= P_1 + P_2,\end{aligned} \tag{5}$$

with the following components,

$$\begin{aligned}\rho_1 &= \frac{V(\phi)\partial_i\phi\partial^i\phi}{\sqrt{1-\partial_i\phi\partial^i\phi}} + \alpha F(H),\\ P_1 &= \beta K(H),\end{aligned} \tag{6}$$

and,

$$\begin{aligned}\rho_2 &= V(\phi)\sqrt{1-\partial_i\phi\partial^i\phi} - \alpha F(H),\\ P_2 &= -V(\phi)\sqrt{1-\partial_i\phi\partial^i\phi} - \beta K(H),\end{aligned} \tag{7}$$

where $F(H)$ and $K(H)$ are arbitrary function of H. Under such splitting we have two-component fluid. First of them describes by EoS (Equation of State) parameter ω_1, which is given by,

$$\omega_1 = \frac{\beta K(H)\sqrt{1-\partial_i\phi\partial^i\phi}}{V(\phi)\partial_i\phi\partial^i\phi + \alpha F(H)\sqrt{1-\partial_i\phi\partial^i\phi}}. \tag{8}$$

EoS parameter for the second component reads as,

$$\omega_2 = \frac{-V(\phi)\sqrt{1-\partial_i\phi\partial^i\phi} - \beta K(H)}{V(\phi)\sqrt{1-\partial_i\phi\partial^i\phi} - \alpha F(H)}, \tag{9}$$

while the total EoS of fluid is

$$\omega = -\big(1-\partial_i\phi\partial^i\phi\big). \tag{10}$$

Equation (10) reduced to $\omega = -(1-\dot{\phi}^2)$ for spatially homogeneous field. Also remember that $\omega \neq \omega_1 + \omega_2$. The species of components of field are recognize by constants α and β. If α and β are both zero then one component is dust matter with zero EoS and other is the cosmological constant (because of its EoS is $\omega = -1$).

For simplicity and as a toy model we will assume that $F(H) = K(H) = H^2$. Alternative models of dark energy suggest a dynamical form of dark energy, which at least in an effective level, can originate from a variable cosmological constant [26, 27], or from various fields, such as a canonical scalar field [28–32] (quintessence), a phantom field [33–39] or the quintom [40–51]. By using some basic of quantum gravitational principles, we can formulate several other models for dark energy and in literature they are known as holographic dark energy paradigm [52–63] and age graphic dark energy models [64–66].

Motivation to consider such splitting is to connect to the attempts of unification of inflation, dark energy and dark matter appearing in literature, which teach us that we can have fluids with exotic EoS, we can consider modified gravity, which already can be accounted as a base to consider fluids with exotic EoS [67–75]. However, in this stage it is to early to conclude that we found a key approach to the unification problem. At least more deep research should be performed, different types of functions should be considered: from linear to some exotic forms not only function on Hubble parameter, but function of scale factor, Ricci scalar or functions of field and potential. We hope that systematic research in this direction, very soon will give desirable results which we will report systematically. We do not exclude possibility that in some cases obtained results will not have deep connection with Universe. Cosmology itself being interdisciplinary research field and a possibility for testing different results has many open questions, which allowed researchers make some phenomenological assumptions which from first sight have not physical bases, but at the same time we observed that with new experimental data old phenomenological assumptions become as a key ingredient of modern Cosmology and found fundamental physical interpretation.

3 Field Equations

Field equations that govern the dynamics of our Universe in frame work of general relativity read as,

$$R^{ij} - \frac{1}{2} g^{ij} R^{k}_{k} = T^{ij}, \tag{11}$$

where T^{ij} is given by (2). We consider the flat FRW Universe with the following metric,

$$ds^2 = dt^2 - a(t)^2 \left(\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2 \theta d\phi^2 \right). \tag{12}$$

In that case the relation (11) gives the following equations,

$$\left(\frac{\dot{a}}{a} \right)^2 = \frac{\rho}{3} - \frac{k}{a^2}, \tag{13}$$

and,

$$-\frac{\ddot{a}}{a} = \frac{1}{6} \left(\rho + 3P + \frac{3k}{a^2} \right). \tag{14}$$

Also Bianchi identities implying that,

$$\dot{\rho} + 3H(\rho + P) = 0, \tag{15}$$

where $8\pi G = c = 1$ and $\Lambda = 0$ assumed. In this paper we consider flat Universe with $k = 0$. The interaction between components formally splits (15) into two equations, with assumptions the transfer of energy from second component to first component, which are given as,

$$\dot{\rho}_1 + 3H(\rho_1 + P_1) = Q, \tag{16}$$

and

$$\dot{\rho}_2 + 3H(\rho_2 + P_2) = -Q. \tag{17}$$

We take interaction strength Q as phenomenological approach,

$$Q = 3bH\rho + \gamma \dot{\rho} \tag{18}$$

where b and γ are constants, bound by observations and $\rho = \rho_1 + \rho_2$, $\dot{\rho} = \dot{\rho}_1 + \dot{\rho}_2$ and $H = \dot{a}/a$ is Hubble parameter. By using this form of interaction strength, the conservation of energy equations are written as,

$$(1-\gamma)\dot{\rho}_1 + 3H\left(1+\omega_1 - b - b\frac{\rho_2}{\rho_1}\right)\rho_1 = \gamma\dot{\rho}_2, \tag{19}$$

and

$$(1+\gamma)\dot{\rho}_2 + 3H\left(1+\omega_2 + b + b\frac{\rho_1}{\rho_2}\right)\rho_2 = -\gamma\dot{\rho}_1. \tag{20}$$

Questions concerning to interacting dark energies are requiring careful approach, because considered forms and types of interactions between components are of phenomenological character. Different interacting models of dark energy have been investigated. As far as we know no known symmetry in nature prevents or suppresses a non-minimal coupling between dark energy and dark matter. At the same time, no piece of evidence has been so far presented against interactions. It is found that a suitable interaction can help to alleviate the coincidence problem. The forms of interaction term considered in literature very often are of the following forms: $Q = 3Hb\rho_{dm}$, $Q = 3Hb\rho_{de}$, or $Q = 3Hb\rho_{tot}$, where b is a coupling constant and positive b means that dark energy decays into dark matter, while negative b means dark matter decays into dark energy. It was found that the observations may favor the decaying of dark matter into dark energy, while the second law of thermodynamics strongly favors dark energy decays into dark matter. Other forms for interaction term considered in literature are $Q = \gamma\dot{\rho}_{dm}$, $Q = \gamma\dot{\rho}_{de}$, $Q = \gamma\dot{\rho}_{tot}$, $Q = 3Hb\rho_i + \gamma\dot{\rho}_i$, where $i = \{dm, de, tot\}$. These kind of interactions are either positive or negative and can not change sign. A sign-changeable interaction [76, 77] could be achieved very simply either considering a possibility of including deceleration parameter,

$$Q = q(\gamma\dot{\rho} + 3bH\rho), \tag{21}$$

where α and β are dimensionless constants, the energy density ρ could be ρ_m, ρ_{de}, ρ_{tot}. q is the deceleration parameter given by,

$$q = -\frac{1}{H^2}\frac{\ddot{a}}{a} = -1 - \frac{\dot{H}}{H^2}. \tag{22}$$

The term of $\gamma\dot{\rho}$ in Q is introduced from the dimensional point of view. In the next section we investigate GSL of thermodynamics in our system.

4 The Generalized Second Law of Thermodynamics

In this section we are going to deal with the question of the validity of the GSL of thermodynamics. For GSL of thermodynamics we will follow Ref. [78], where was considered validity of the GSL of thermodynamics for the Universe bounded by the Hubble horizon,[1]

$$R_H = \frac{1}{H}, \tag{23}$$

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[1] Recall that in case when $k = 0$ as in our case apparent horizon $R_A = \frac{1}{\sqrt{H^2 + \frac{k}{a^2}}}$ we get the radius of the Hubble horizon (23).

cosmological event horizon,

$$R_E = a\int_t^\infty \frac{dt}{a}, \tag{24}$$

and the particle horizon,

$$R_P = a\int_0^t \frac{dt}{a}. \tag{25}$$

The contents in the Universe bounded by the event horizons taken as interacting two components of a single scalar field. The foundation of GSL required the following Gibbs equation of thermodynamics satisfied,

$$T_X dS_{IX} = PdV_X + dE_{IX} \tag{26}$$

where S_{IX} and $E_{IX} = \rho V_X$, are internal entropy and energy within the horizon respectively, while $V_X = \frac{4}{3}\pi R_X^3$ denotes the volume of sphere with the horizon radius R_A. Recall that GSL together with the first law of thermodynamics for the time derivative of total entropy gives,

$$\dot{S}_X + \dot{S}_{IX} = \frac{R_X^2}{GT_X}\left(\frac{k}{a^2} - \dot{H}\right)\dot{R}_X, \tag{27}$$

while in the case of without the first law we get,

$$\dot{S}_X + \dot{S}_{IX} = \frac{2\pi R_X}{G}\left[R_X^2\left(\frac{k}{a^2} - \dot{H}\right)(\dot{R}_X - HR_X) + \dot{R}_X\right]. \tag{28}$$

Under the notations used above we understood that $T_X = \frac{1}{2\pi R_X}$ and R_X is temperature and radius for a given horizon under equilibrium thermodynamics respectively, S_X is the horizon entropy and $\dot{S}_{IX}$ as the rate of change of internal entropy. It was found that the first and second laws of thermodynamics hold on the apparent horizon when the apparent horizon and the event horizon of the Universe are different, while for consideration of only event horizon these laws breakdown [79]. The Friedmann equations and the first law of thermodynamics (on the apparent horizon) are equivalent if the Universe is bounded by the apparent horizon R_A with temperature $T_A = \frac{1}{2\pi R_A}$ and entropy $S_A = \frac{\pi R_A}{G}$. Usually, the Universe bounded by apparent horizon and in this region the Bekenstein's entropy-mass bound ($S \leq 2\pi E R_A$) and entropy—area bound ($S \leq \frac{A}{4}$) are hold. Numerical analysis of (27) and (28) given in the Sect. 6. In order the GSL to be hold it is required that $\dot{S}_X + \dot{S}_{IX} \geq 0$ i.e. the sum of entropy of matter enclosed by horizon must be not be a decreasing function of time.

5 Statefinder Diagnostics

In this section we consider problem of statefinder diagnostics. The property of dark energy is model dependent and to differentiate various models of dark energy, a sensitive diagnostic tool is needed. Hubble parameter H and deceleration parameter q are very important quantities which can describe the geometric properties of the Universe. Since $\dot{a} > 0$, hence $H > 0$ means the expansion of the Universe. Also, $\ddot{a} > 0$, which is $q < 0$ indicates the accelerated expansion of the universe. Since, the various dark energy models give $H > 0$ and $q < 0$, they can not provide enough evidence to differentiate the more accurate cosmological observational data and the more general models of dark energy. For this aim we need higher order of

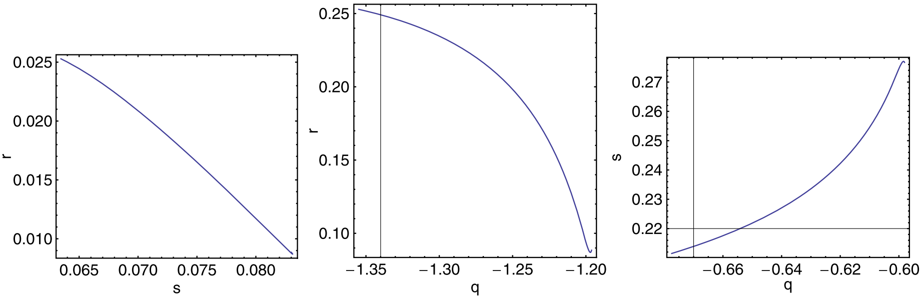


Fig. 1 The above plot refer to the links between r, s and q. We choose $\alpha = 2.5$, $\beta = 1.5$, $b = 0.01$ and $\gamma = 0.02$

time derivative of scale factor and geometrical tool. Sahni *et al.* [79] proposed geometrical statefinder diagnostic tool, based on dimensionless parameters (r, s) which are function of scale factor and its time derivative. These are jerk and snap parameters which are define as the following,

$$r = \frac{1}{H^3}\frac{\dddot{a}}{a}, \qquad s = \frac{r-1}{3(q-\frac{1}{2})}, \tag{29}$$

respectively. The deceleration parameter is also given by (22). We will use other form of parameters in terms of he total energy density ρ and pressure P in the Universe,

$$r = 1 + \frac{9(\rho + P)}{2\rho}\frac{\dot{P}}{\dot{\rho}}, \qquad s = \frac{(\rho + P)}{P}\frac{\dot{P}}{\dot{\rho}}, \qquad q = \frac{1}{2}\left(1 + \frac{3P}{\rho}\right). \tag{30}$$

The plot of r, s and q are given in the Fig. 1.

6 Numerical Results

Numerical analysis provide us following information. First of all we find that field is a complex one and in this case a complex field is able to produce accelerated expansion i.e $q < 0$. In the Fig. 2 we present behavior of $\omega_{eff} = \frac{P_1+P_2}{\rho_1+\rho_2}$ of composed fluid, ω_1, ω_2 of fluids and q against time t for different values of α and β with the fixed valued of interacting constants. We observe that for the composed fluid for early stages of evolution it is a fluid with $\omega > 0$ but then we have transition to a dark energy with $\omega > -1$ indicating quintessence-like behavior. We also investigate behavior of ω_1 and ω_2 of our phenomenological fluids and observe that ω_1 is a positive at early stages and carries fast jump to a dark energy with negative EoS parameter (phantom dark energy) and then during evolution it becomes quintessence with $\omega > -1$. Fast change of the type of the first fluid can have very deep physics. In this letter we assume that, or this behavior related to the fact that Tachyon field is unstable in early

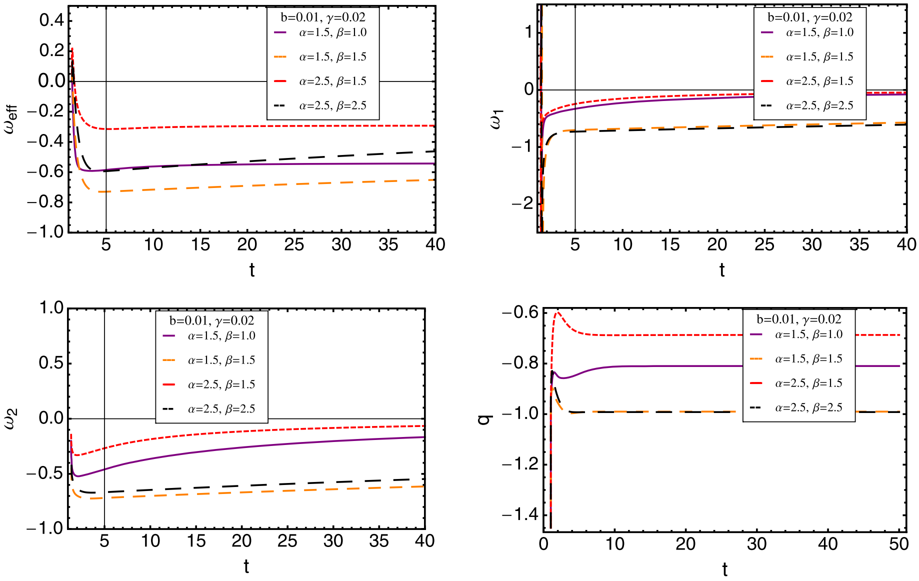


Fig. 2 The above plots refer to the links between ω_{tot}, ω_1, ω_2, q and t for fixed interaction parameters. In $(q - t)$ plot, it is seen that the Universe initially undergoes a rapidly falling acceleration followed by a rise in it. At a particular epoch the Universe get into a phase of constant acceleration in which we are presently located. We choose $b = 0.01$ and $\gamma = 0.02$

stages of evolution, either that first fluid itself is not in thermodynamical equilibrium and some irreversible processes like to a particle creation and annihilation is happening "inside" the fluid. More deep analysis is needed in order to conclude with right physics. On the other hand, we see that ω_2 is completely negative for all values of our parameters $(0 > \omega > -1)$ which suggest quintessence-like behavior. For the deceleration parameter we see, that it is negative i.e. we get ever accelerated Universe.

In the second analysis of the model, for illustration, we fixed values of parameters coming from fluids splitting i.e. α and β and investigate behavior of EoS parameters and q against time for different values of interacting constants (see Fig. 3). We conclude that, for different values of interaction parameters intensively considered in literature discussed from experimental constraints, composed fluid and its components can be identified as the same and first fluid has the same behavior as already discussed above i.e fast transition from a fluid to a dark energy at early stages of evolution. Again, we have ever accelerated Universe.

Validity of the GSL of thermodynamics is satisfied for our model, which can be accounted as a simple and first test telling us about true-like model (see Fig. 4). Other test like comparing the model with experimental data can be also done in future, which is also will allow us to fix a viable range of the values of the model.

Finally in the Fig. 5 we present $V(t)$ and $\phi(t)$. We can see that there is a maximum for the potential which is corresponding to the minimum of the ω_{eff}. Then, Tachyon potential vanished at the late time, which is expected. We find that increasing β increased potential while increasing α decreased one. Also we see that ϕ is increasing function of time at the late time, while in the early stage it is strongly depend on choosing parameters. We can observe that the parameter β decreases value of ϕ at the late stage but the parameter α increases one.

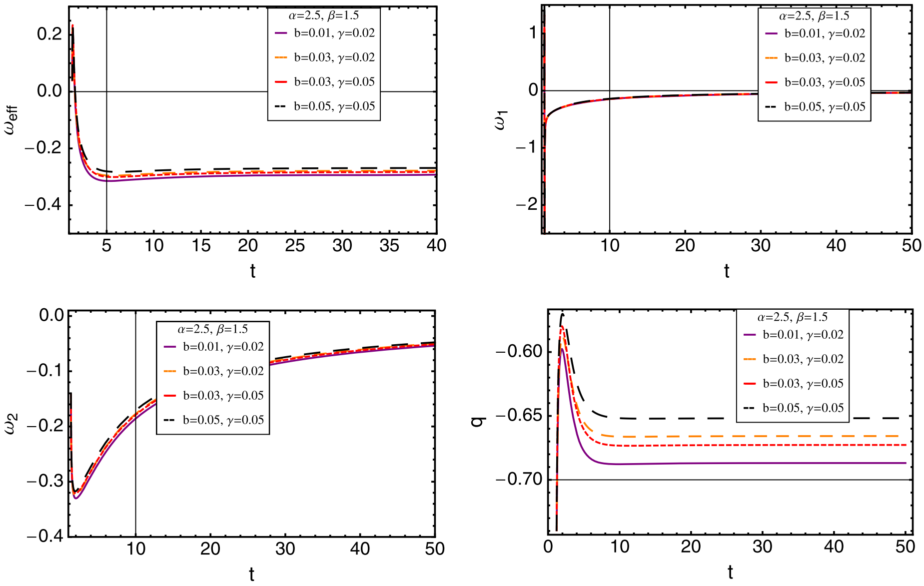


Fig. 3 The above plots refer to the links between ω_{tot}, ω_1, ω_2, q and t for fixed fluid parameters. In $(q-t)$ plot, it is seen that the Universe initially undergoes a rapidly falling acceleration followed by a rise in it. At a particular epoch the Universe get into a phase of constant acceleration in which we are presently located. We choose $\alpha = 2.5$ and $\beta = 1.5$

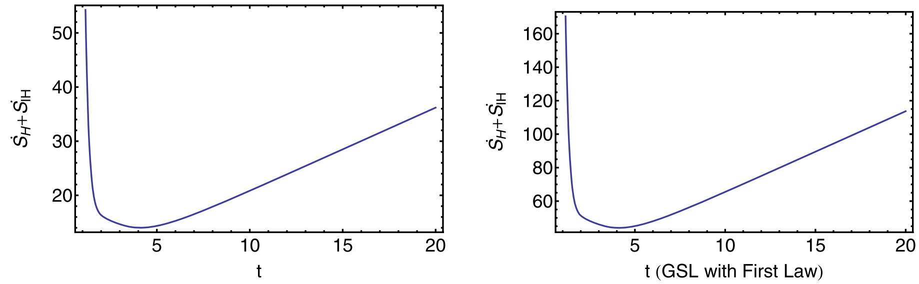


Fig. 4 $\dot{S}_H + \dot{S}_{IH}$ versus time for the case of, *Left*: only GSL of thermodynamics (without the first law). *Right*: GSL together with the first law of thermodynamics. We set $\alpha = 2.5$, $\beta = 1.5$, $b = 0.01$ and $\gamma = 0.02$

7 Time-Dependent Densities

After numerical analysis of our model, now we present some analytical studies under special assumptions which help us to obtain solutions of coupled equations (19) and (20). First of all we assume well known form of Hubble expansion parameter as $H = h/t$ [80, 81], where h is a constant which will be fixed by using observational data, and one can find $q = -1 + \frac{1}{h}$. Also, we fix parameters as $b = \gamma(1 + \omega_2)$. Under these assumption we can solve coupled equations (19) and (20) to obtain the following time-dependent densities,

$$\rho_1 = \rho(0)t^{-3h(1+\omega_1+\gamma(\omega_1-\omega_2))}, \tag{31}$$

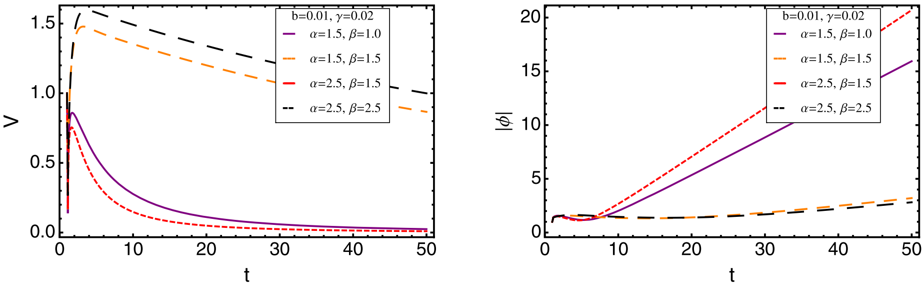


Fig. 5 Plots of $V(t)$ and $\phi(t)$, where we choose $b = 0.01$ and $\gamma = 0.02$

and,

$$\rho_2 = \rho(0)t^{-\frac{3h(1+\omega_2+\gamma(1+\omega_2))}{1+\gamma}} \times \left[1 - \frac{(1-\gamma)\gamma}{(1+\gamma)^2} t^{-3h(1+\gamma)(\omega_1-\omega_2)}\right], \tag{32}$$

where we assumed current values of densities as an equal constant $\rho_1(0) = \rho_2(0) = \rho(0)$.

At the late time, where $\omega_1 \approx \omega_2 = \omega_0$, one can obtain the following total density,

$$\rho = \rho(0)t^{-\frac{3h(1+\omega_0+\gamma(1+\omega_0))}{1+\gamma}}, \tag{33}$$

and total pressure,

$$P = P(0)t^{-\frac{3h(1+\omega_0+\gamma(1+\omega_0))}{1+\gamma}}, \tag{34}$$

where current value of pressure defined as $P(0) = \omega_0\rho(0)$. In the next section we use observational data to fix solution.

8 Observational Data

In the previous section we used specific form of Hubble expansion parameter ($H = h/t$) which yields to the scale factor of the form $a(t) = a(0)t^h$. These assumptions give us solution depend on parameter h which may be fixed by observational data. In order to fix the scale factor, we use the declaration parameter q.

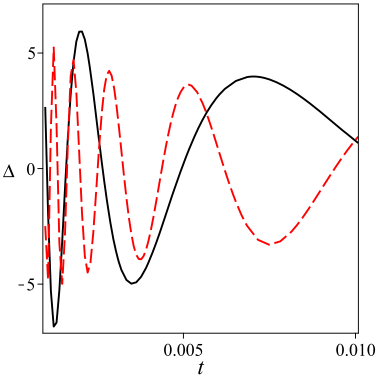
According to the SNeIa observational data [82] the current value of the declaration parameter may be $q_0 = -1$ satisfied by using large h. In that case we yield to $\rho \ll 1$ which agree with current observational data.

On the other hand from the Λ-CDM observational data [83] the current value of the declaration parameter may be $q_0 = -0.6$, which yields to $h = 2.5$

Also, according to the best fitted parameters, it is $q_0 = -0.64$, which yields to $h = 2.77$ to obtain agreement with observational data.

Finally according to the recent observational data of the Refs. [84, 85] $q_0 = -0.53$, which yields to $h = 2.127659574$. Therefore in order to obtain expanding Universe with negative q it should be $h > 1$ so we found that $2 < h < 3$ is logical choice.

Fig. 6 Δ versus time for the special case with $\omega_0 = -0.1$ (*black solid*) and $\omega_0 = -0.01$ (*red dashed*)
(Color figure online)



9 Linear Perturbation and Stability

In the previous section we obtained energy densities and therefore pressure. Hence, one can investigate stability of theory via sound speed,

$$C_s^2 = \frac{\dot{P}}{\dot{\rho}}, \tag{35}$$

so $C_s^2 \geq 0$ yield to stability of theory. By using result of previous section we find that the condition $\omega_1 \geq \omega_2$ yields to $C_s^2 \geq 0$ and therefore stable theory. However the speed of sound is not enough to verity stability of system. There are several ways to investigate stability of a theory such as evolution of density perturbations which yields to the following differential equation,

$$\ddot{\Delta} + 2H\dot{\Delta} - \left(\frac{\rho}{2} - \frac{C_s^2}{a^2}\right)\Delta = 0, \tag{36}$$

where $\Delta \equiv \delta\rho/\rho$. In the special case of late time with $\omega_1 = \omega_2 = \omega_0$ we can find Δ proportional to Bessel function J and Y as,

$$\Delta = t^{\frac{1}{2}-h}\left[C_1 BesselJ\left(\nu, \mu(t)\right) + C_2 BesselY\left(\nu, \mu(t)\right)\right], \tag{37}$$

where C_1 and C_2 are arbitrary constants and,

$$\nu \equiv -\frac{\sqrt{4(h-\frac{1}{2})^2 a(0)^2 - 4\omega_0}}{a(0)(3h + 3h\omega_0 - 2)}, \tag{38}$$

and,

$$\mu \equiv \frac{\sqrt{2}}{3h + 3h\omega_0 - 2} t^{1-\frac{3}{2}h(1+\omega_0)}, \tag{39}$$

are defined. This show damping periodic picture as illustrated in the Fig. 6. General solution of (36) also has similar behavior which illustrated in the Fig. 7. In order to draw Figs. 6 and 7 we choose $\Delta(0) = 0$ and $\dot{\Delta}(0) = 1$.

As we expected from potential analysis there is stability in the late time, while in the early time our theory is unstable and tachyon state may decay to another state.

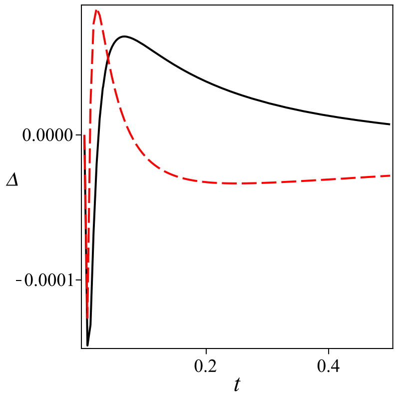


Fig. 7 Δ versus time for the general case with $\omega_1 = -0.5$, $\omega_2 = -0.2$ (*black solid*) and $\omega_2 = -0.5$, $\omega_1 = -0.2$ (*red dashed*) (Color figure online)

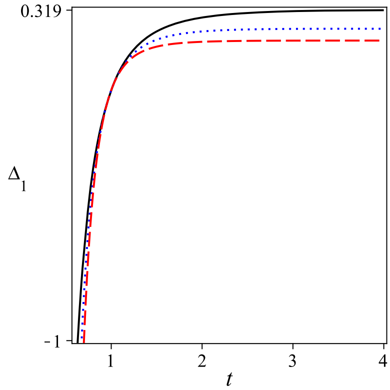


Fig. 8 Δ_1 versus time for the general case with $\omega_1 = -0.5$, $\omega_2 = -0.2$, $b = 0.01$ and $\gamma = 0.02$. $h = 2$ (*black solid*), $h = 2.5$ (*blue dotted*), $h = 3$ (*red dashed*) (Color figure online)

It is also interesting to separate (36) to its components and investigate stability of both components separately,

$$\ddot{\Delta}_1 + 2H\dot{\Delta}_1 - \left(\frac{\rho_1}{2} - \frac{C_{s1}^2}{a^2}\right)\Delta_1 = 0, \tag{40}$$

$$\ddot{\Delta}_2 + 2H\dot{\Delta}_2 - \left(\frac{\rho_2}{2} - \frac{C_{s2}^2}{a^2}\right)\Delta_2 = 0, \tag{41}$$

where $C_{s1}^2 = \frac{\dot{P}_1}{\dot{\rho}_1}$ and $C_{s2}^2 = \frac{\dot{P}_2}{\dot{\rho}_2}$. We solve (40) numerically and draw Δ_1 in the Fig. 8 which show over-damping feature. In this figure we vary h between 2 and 3 and find that increasing h decreases Δ_1. Also we solve equation (41) numerically and draw Δ_2 in the Fig. 9 which show under-damping feature for smaller values of h (black line) and slowly-damping feature for larger h.

10 Conclusion

In this article we considered a phenomenological splitting of Tachyonic scalar field which gives rise of two fluids. On the base of special form of additional term, which is a function of Hubble parameter with an interaction between them we investigated behavior of the

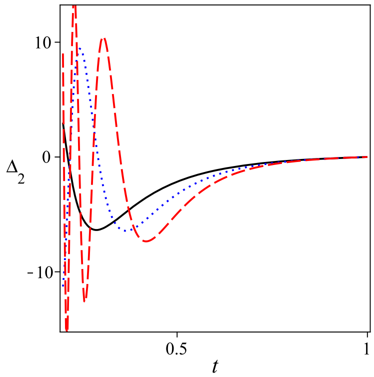


Fig. 9 Δ_2 versus time for the general case with $\omega_1 = -0.5$, $\omega_2 = -0.2$, $b = 0.01$ and $\gamma = 0.02$. $h = 2$ (*black solid*), $h = 2.5$ (*blue dotted*), $h = 3$ (*red dashed*)
(Color figure online)

Universe. We observed that we have ever accelerated expansion. Fluid responsible for that acceleration for later stages is dark energy with $\omega < 0$, while for early stages of evolution it was not dark energy, moreover we have fluid type transition. This behavior can be accepted as counterintuitive related to the fact that, in GR, accelerated expansion caused by dark energy. GR does not give any explanation related to the origin of dark energy as well as about origin of dark meter. Numerical analysis shows that field is a complex and is able to provide discussed acceleration.

For the well known form oh Hubble expansion parameter and specific fixed value of interaction parameter we succeed to decouple conservation equations and obtain time-dependent densities. These help us to study first order linear perturbation and investigate stability of our model. We conclude that our model is unstable in early Universe, but translate to stable phase after few time.

Validity of the GSL of thermodynamics could be thought as a test giving us a hope, that we could continue our research in this direction. We already mentioned about motivations and about our interests related to the question, which is arose from the research providing different ways for unification of inflation, dark energy and dark matter, which provides us knowledge that we have a right to consider fluids with exotic EoS like in our case, with one difference that the base of our fluids is Tachyonic field. In future we would like to consider different variations concerning to the forms of functions and parameters and investigate behavior of the Universe and fluid. Also, one can investigate the effects of shear or bulk viscosities on the system.

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