Interacting tachyon dark energy in non-flat universe

M. R. Setare\textsuperscript{a} *, J. Sadeghi\textsuperscript{b}† and A. R. Amani\textsuperscript{c}‡

\textsuperscript{a}Department of Science, Payame Noor University, Bijar, Iran
\textsuperscript{b}Sciences Faculty, Department of Physics, Mazandaran University,
P.O.Box 47415-416, Babolsar, Iran
\textsuperscript{c}Department of Physics, Islamic Azad University - Ayatollah Amoli Branch,
P.O.Box 678, Amol, Iran

March 5, 2009

Abstract

In this paper we study the tachyon cosmology in non-interacting and interacting cases in non-flat FRW universe. Then we reconstruct the potential and the dynamics of the tachyon field which describe tachyon cosmology.

1 Introduction

Nowadays it is strongly believed that the universe is experiencing an accelerated expansion. Recent observations from type Ia supernovae \textsuperscript{[1]} in association with Large Scale Structure \textsuperscript{[2]} and Cosmic Microwave Background anisotropies \textsuperscript{[3]} have provided main evidence for this cosmic acceleration. In order to explain why the cosmic acceleration happens, many theories have been proposed. Although theories of trying to modify Einstein equations constitute a big part of these attempts, the mainstream explanation for this problem, however, is known as theories of dark energy. It is the most accepted idea that a mysterious dominant component, dark energy, with negative pressure, leads to this cosmic acceleration, though its nature and cosmological origin still remain enigmatic at present.

The most obvious theoretical candidate of dark energy is the cosmological constant $\lambda$ (or vacuum energy) \textsuperscript{[4, 5]} which has the equation of state $\omega = -1$. An alternative proposal for dark energy is the dynamical dark energy scenario. So far, a large class of scalar-field dark energy models have been studied, including quintessence \textsuperscript{[6]}, K-essence \textsuperscript{[7]}, tachyon \textsuperscript{[8]},

\textsuperscript{*}Email: rezakord@ipm.ir
\textsuperscript{†}Email: pouriya@ipm.ir
\textsuperscript{‡}Email: a.r.amani@iauamol.ac.ir
phantom [9], ghost condensate [10,11] and quintom [12], interacting dark energy models [13], braneworld models [14], and Chaplygin gas models [15], etc. An interacting tachyonic-dark matter model has been studied in Ref. [16].

In this paper, we consider the issue of the tachyon as a source of the dark energy. The tachyon is an unstable field which has become important in string theory through its role in the Dirac-Born-Infeld (DBI) action which is used to describe the D-brane action [17,18]. It has been noticed that the cosmological model based on effective lagrangian of tachyon matter

\[ L = -V(T) \sqrt{1 - T_{\mu}T^{\mu}} \]  

with the potential \( V(T) = \sqrt{A} \) exactly coincides with the Chaplygin gas model [19,20]. Some experimental data have implied that our universe is not a perfectly flat universe and recent papers have favoured a universe with spatial curvature [21]. As a matter of fact, we want to remark that although it is believed that our universe is flat, a contribution to the Friedmann equation from spatial curvature is still possible if the number of e-foldings is not very large [22]. Cosmic Microwave Background (CMB) anisotropy data provide the most stringent constraints on cosmic curvature \( k \). Assuming that dark energy is a cosmological constant, the three-year WMAP data give \( \Omega_k = -0.15 \pm 0.11 \), and this improves dramatically to \( \Omega_k = -0.005 \pm 0.006 \), with the addition of galaxy survey data from the SDSS [23]. The effect of allowing non-zero curvature on constraining some dark energy models has been studied by [24]. Recently Clarkson et al [25] have shown that ignoring \( \Omega_k \) induces errors in the reconstructed dark energy equation of state, \( \omega(z) \), that grow very rapidly with redshift and dominate the \( \omega(z) \) error budget at redshifts \( (z \gtrsim 0.9) \) even if \( \Omega_k \) is very small. Due to these considerations and motivated by the recent work of Chakraborty and Debnath [26], we generalize their work to the non-flat case.

## 2 Tachyonic fluid model

Now we consider the single tachyonic field model, so the action for the homogeneous tachyon condensate of string theory in a gravitational background is given by

\[ S = \int d^4x \sqrt{-g} \left[ \frac{R}{16\pi G} + \mathcal{L} \right] \]  

where \( R \) and \( \mathcal{L} \) are scalar curvature and Lagrangian density respectively, \( \mathcal{L} \) is given by,

\[ \mathcal{L} = -V(T) \sqrt{1 + g^{\mu\nu} \partial_\mu T \partial_\nu T}, \]  

where \( T \) is tachyon field, and \( V(T) \) is the tachyonic potential. The Friedmann-Robertson-Walker (FRW) metric of universe is as,

\[ ds^2 = dt^2 - a^2(t) \left[ \frac{dr^2}{1 - kr^2} + r^2 d\Omega^2 \right], \]
here $k = 1, 0, -1$ are corresponds to closed, flat and open universe respectively. By using the Einstein’s equation we have following expression

$$\rho_{tot} = \frac{3}{2} \left( \frac{\dot{a}^2}{a^2} + \frac{k}{a^2} \right),$$

where we have assumed $4\pi G = 1$. On the other hand, the energy-momentum tensor for the tachyonic field is,

$$T_{\mu\nu} = \frac{2}{\sqrt{-g}} \frac{\delta S}{\delta g_{\mu\nu}} = p_T g_{\mu\nu} + (p_T + \rho_T) u_\mu u_\nu,$$

where the velocity $u_\mu$ is

$$u_\mu = -\frac{\partial_\mu T}{\sqrt{-g} \partial_\mu T},$$

with $u^\mu u_\mu = -1$.

By using the energy-momentum tensor we have following expressions

$$R = 6 \left( \frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a^2} + \frac{k}{a^2} \right),$$

$$\rho_T = \frac{V(T)}{\sqrt{1 - T^2}}, \quad p_T = -V(T) \sqrt{1 - T^2}.$$

Thus the equation of states of tachyonic field becomes

$$\omega_T = \frac{p_T}{\rho_T} = \dot{T}^2 - 1,$$

$$p_T \rho_T = -V^2(T),$$

Now we consider two fluid model consisting of tachyonic field and barotropic fluid respectively. The EoS of the barotropic fluid is given by

$$p_b = \omega_b \rho_b,$$

where $p_b$ and $\rho_b$ are the pressure and energy density of barotropic fluid. Thus, the total energy density and pressure are respectively given by,

$$\rho_{tot} = \rho_b + \rho_T,$$

$$p_{tot} = p_b + p_T,$$

In the next following section we consider two cases, first we investigate the case where two fluid do not interact with each other and second we consider interacting case.
3 Non-interacting two fluids model

In this section we assume that two fluid do not interact with each other. As we know the general form of conservation equation is

\[
\dot{\rho}_{\text{tot}} + 3\frac{\dot{a}}{a}(\rho_{\text{tot}} + p_{\text{tot}}) = 0,
\]

this equation lead us to write the conservation equation for the tachyonic and barotropic fluid separately,

\[
\dot{\rho}_b + 3\frac{\dot{a}}{a}(\rho_b + p_b) = 0,
\]

and

\[
\dot{\rho}_T + 3\frac{\dot{a}}{a}(\rho_T + p_T) = 0.
\]

By using the equation (17) one can obtain the energy density \(\rho_b\) as a follow,

\[
\rho_b = \rho_0 a^{-3(1+\omega_b)}.
\]

In order to obtain \(T\) and \(V(T)\) we first obtain the \(\rho_T\) and \(p_T\) in term of \(a(T)\),

\[
\rho_T = \frac{3}{2} \left( \frac{\dot{a}^2}{a^2} + \frac{k}{a^2} \right) - \rho_0 a^{-3(1+\omega_b)},
\]

and

\[
p_T = -\frac{1}{2} \left( \frac{2\ddot{a}}{a} + \frac{\dot{a}^2}{a^2} + \frac{k}{a} \right) - \rho_0 \omega_b a^{-3(1+\omega_b)},
\]

Here by using the equation (18), (20) and (21) the corresponding field for the tachyon will be as

\[
\dot{T} = \sqrt{\frac{\frac{\dot{a}^2}{a^2} + \frac{k}{a^2} - \frac{\ddot{a}}{a} - \rho_0 (1 + \omega_b) a^{-3(1+\omega_b)}}{\frac{3}{2} \left( \frac{\dot{a}^2}{a^2} + \frac{k}{a^2} \right) - \rho_0 a^{-3(1+\omega_b)}}},
\]

and from equation (12), the \(V(T)\) is given by,

\[
V(T) = \sqrt{\left[ \frac{1}{2} \left( \frac{\dot{a}^2}{a^2} + \frac{k}{a^2} + 2\frac{\dot{a}}{a} \right) + \rho_0 \omega_b a^{-3(1+\omega_b)} \right] \left[ \frac{3}{2} \left( \frac{\dot{a}^2}{a^2} + \frac{k}{a^2} \right) - \rho_0 a^{-3(1+\omega_b)} \right]},
\]

Now we take following ansatz for the scale factor, where increase in term of time evolution

\[
a(t) = \sqrt{bk + c \cosh^2(\beta t)},
\]

where \(b, c\) and \(\beta\) are constant. By substituting above scale factor into (20) and (21) the \(\rho_T\) and \(p_T\) can be given by following expression,

\[
\rho_T = \frac{3}{2} \frac{c \cosh^2(\beta t) \left( c \beta^2 \sinh^2(\beta t) - k \right) + 3k^2 b}{(bk + c \cosh^2(\beta t))^2 - \rho_0 (bk + c \cosh^2(\beta t))^{-\frac{3}{2}(1+\omega_b)}}
\]
and
\[ p_T = -\frac{1}{2} \cosh^2(\beta t) \left[ 3c^2 b^2 \cosh^2(\beta t) - c^2 \beta^2 + kc + 4ck \beta^2 \right] - 2ck \beta^2 + k^2 b \]
\[ \frac{(bk + c \cosh^2(\beta t))^2}{2} \]
\[ -\rho_0 \omega_b \left( bk + c \cosh^2(\beta t) \right)^{-\frac{2}{3}(1+\omega_b)} \]  
(26)

By putting the \( \rho_T \) and \( p_T \) in equation \( \dot{T} = \sqrt{1 + \frac{\rho_T}{p_T}} \) and drawing the corresponding \( \dot{T} \) in term of time, we obtain \( \dot{T} = \delta \sech(\eta t) \) where \( \delta \) and \( \eta \) are given in term of \( b, c \) and \( \beta \). Then we have,
\[ T = \frac{\delta}{\eta} \arctan(\sinh(\eta t)), \]  
(27)

Also, the corresponding potential Eq. (23) will be form of \( A + Be^{-Ct^2} \). Now one can use Eq. (27) and reconstruct potential \( V \), in term of tachyon field \( T \), as following
\[ V(T) = A + B e^{-\frac{C}{\eta^2} \left( \arcsinh(\tan(\frac{T}{\eta})) \right)^2}, \]  
(28)

By substituting Eqs. (25) and (26) in (11), one can obtain the equation of state of tachyon field in term of time. The graph of this EoS in term of time evolution is given by Fig. (1).

![Figure 1: The EoS is plotted in \( \rho_0 = -30, c = 20, b = 0.5, \beta = 0.75 \), and \( k = +1, 0, -1 \) as the solid, dot and dash respectively.](image)

4 Interaction two fluids model

Now we are going to consider an interaction between the tachyonic field and the barotropic fluid. Here we need to introduce a phenomenological coupling function which is a product of the Hubble parameter and the energy density of the barotropic fluid. In that case there is an energy flow between the two fluid. so, the equation of motion corresponding to the tachyonic field and the barotropic fluid are respectively,
\[ \dot{\rho}_T + 3 \frac{\dot{a}}{a}(\rho_T + p_T) = -Q, \]  
(29)
\[
\dot{\rho}_b + 3\frac{\dot{a}}{a}(\rho_b + p_b) = Q,
\]

where the quantity \( Q \) expresses the interaction between the dark components. The interaction term \( Q \) should be positive, i.e. \( Q > 0 \), which means that there is an energy transfer from the dark energy to dark matter. The positivity of the interaction term ensures that the second law of thermodynamics is fulfilled \([27]\). At this point, it should be stressed that the continuity equations imply that the interaction term should be a function of a quantity with units of inverse of time (a first and natural choice can be the Hubble factor \( H \)) multiplied with the energy density. Therefore, the interaction term could be in any of the following forms: (i) \( Q \propto H \rho_T \) \([28, 27]\), (ii) \( Q \propto H \rho_b \) \([29]\), or (iii) \( Q \propto H (\rho_T + \rho_b) \) \([30]\). The freedom of choosing the specific form of the interaction term \( Q \) stems from our incognizance of the origin and nature of dark energy as well as dark matter. Moreover, a microphysical model describing the interaction between the dark components of the universe is not available nowadays. Here we consider \( Q = 3H \sigma \rho_b \), where \( \sigma \) is a coupling constant. By using the equations \([29]\) and \([30]\) one can obtain the \( \rho_b, \rho_T \) and \( p_T \) as a following,

\[
\rho_b = \rho_0 a^{-3(1+\omega_b-\sigma)},
\]

\[
\rho_T = \frac{3}{2} \left( \frac{\ddot{a}}{a^2} + \frac{k}{a^2} \right) - \rho_0 a^{-3(1+\omega_b-\sigma)},
\]

and

\[
p_T = -\frac{1}{2} \left( \frac{\ddot{a}}{a} + \frac{\ddot{a}}{a^2} + \frac{k}{a^2} \right) - \rho_0 (\omega_b - \sigma) a^{-3(1+\omega_b-\sigma)}.
\]

Similar to previous case the \( \dot{T} \) and \( V(T) \) can be obtained by the following expression,

\[
\dot{T} = \sqrt{1 - \frac{1}{2} \left( \frac{\ddot{a}}{a} + \frac{\ddot{a}}{a^2} + \frac{k}{a^2} \right) + \rho_0 (\omega_b - \sigma) a^{-3(1+\omega_b-\sigma)}} - \frac{3}{2} \left( \frac{\ddot{a}}{a^2} + \frac{k}{a^2} \right) - \rho_0 a^{-3(1+\omega_b-\sigma)},
\]

and

\[
V(T) = \sqrt{\left[ \frac{1}{2} \left( \frac{\ddot{a}}{a} + \frac{\ddot{a}}{a^2} + \frac{k}{a^2} \right) + \rho_0 (\omega_b - \sigma) a^{-3(1+\omega_b-\sigma)} \right] \left[ \frac{3}{2} \left( \frac{\ddot{a}}{a^2} + \frac{k}{a^2} \right) - \rho_0 a^{-3(1+\omega_b-\sigma)} \right]}.
\]

Putting the value of \( a(t) \) from equation \([24]\) in \( \rho_T, p_T, \dot{T} \) and \( V \) we have,

\[
\rho_T = \frac{3c^2 \cosh^2(\beta t) \left( c \beta^2 \sinh^2(\beta t) - k \right) + 3k^2 b}{2 \left( bk + c \cosh^2(\beta t) \right)^2}
\]

\[
- \rho_0 \left( bk + c \cosh^2(\beta t) \right)^{-\frac{3}{2}(1+\omega_b-\sigma)}
\]

and

\[
p_T = -\frac{1}{2} \left( \frac{\cosh^2(\beta t)}{2} \left[ 3c^2 \beta^2 \cosh^2(\beta t) - c^2 \beta^2 - 4ckb \beta^2 \right] - 2ckb \beta^2 + k^2 b \right)
\]

\[
(bk + c \cosh^2(\beta t))^2
\]

\[
- \rho_0 (\omega_b - \sigma) \left( bk + c \cosh^2(\beta t) \right)^{-\frac{3}{2}(1+\omega_b-\sigma)}
\]
By substituting the $\rho_T$ and $p_T$ in equation $\dot{T} = \sqrt{1 + \frac{p_T}{\rho_T}}$ and drawing the corresponding $\dot{T}$ in term of time we have graphs of $T$ and $V$ as the same results with non-interaction case. By substituting Eqs. (36) and (37) in (11), graphs of the EoS are given in term of time evolution in Fig. (2).

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{fig2a}
\includegraphics[width=0.4\textwidth]{fig2b}
\caption{The EoS is plotted in $\rho_0 = -30$, $c = 20$, $b = 0.5$, $\beta = 0.75$, $\sigma = 0.25$ and $k = +1, 0, -1$ as the solid, dot and dash respectively.}
\end{figure}

5 Conclusion

Within the different candidates to play the role of the dark energy, tachyon, has emerged as a possible source of dark energy for a particular class of potentials [31]. In the present paper we have studied the tachyonic field model in non-flat universe. At first we have considered the non-interacting case, where the tachyon field and barotropic fluid separately satisfy the conservation equation. We have obtained the evaluation of scale factor, energy density, pressure, tachyon field and potential of tachyon field in term of cosmic time. After that we have reconstruct the potential of tachyon in term of tachyon field. The evaluation of EoS, and the late time behavior of this equation is given by fig 1.

Studying the interaction between the dark energy and ordinary matter will open a possibility of detecting the dark energy. It should be pointed out that evidence was recently provided by the Abell Cluster A586 in support of the interaction between dark energy and dark matter [32]. However, despite the fact that numerous works have been performed till now, there are no strong observational bounds on the strength of this interaction [33]. This weakness to set stringent (observational or theoretical) constraints on the strength of the coupling between dark energy and dark matter stems from our unawareness of the nature and origin of dark components of the Universe. It is therefore more than obvious that further work is needed in this direction. Due to this we have extended the our consideration to the interacting case in a separate section of this paper.

6 Acknowledgement

The authors would like to thank an anonymous referee for crucial remarks and advices.
References

[1] A. G. Riess et al. [Supernova Search Team Collaboration], Astron. J. 116, 1009 (1998) astro-ph/9805201;
S. Perlmutter et al. [Supernova Cosmology Project Collaboration], Astrophys. J. 517, 565 (1999) astro-ph/9812133;
P. Astier et al., Astron. Astrophys. 447, 31 (2006) astro-ph/0510447.

[2] K. Abazajian et al. [SDSS Collaboration], Astron. J. 128, 502 (2004) astro-ph/0403325;
K. Abazajian et al. [SDSS Collaboration], Astron. J. 129, 1755 (2005) astro-ph/0410239.

[3] D. N. Spergel et al. [WMAP Collaboration], Astrophys. J. Suppl. 148, 175 (2003) astro-ph/0302209;
D. N. Spergel et al., astro-ph/0603449.

[4] A. Einstein, Sitzungsber. K. Preuss. Akad. Wiss. 142 (1917) [The Principle of Relativity (Dover, New York, 1952), p. 177].

[5] S. Weinberg, Rev. Mod. Phys. 61 1 (1989);
V. Sahni and A. A. Starobinsky, Int. J. Mod. Phys. D 9, 373 (2000) astro-ph/9904398;
S. M. Carroll, Living Rev. Rel. 4 1 (2001) astro-ph/0004075;
P. J. E. Peebles and B. Ratra, Rev. Mod. Phys. 75 559 (2003) astro-ph/0207347;
T. Padmanabhan, Phys. Rept. 380 235 (2003) hep-th/0212290.

[6] P. J. E. Peebles and B. Ratra, Astrophys. J. 325 L17 (1988);
B. Ratra and P. J. E. Peebles, Phys. Rev. D 37 3406 (1988);
C. Wetterich, Nucl. Phys. B 302 668 (1988);
J. A. Frieman, C. T. Hill, A. Stebbins and I. Waga, Phys. Rev. Lett. 75, 2077 (1995) astro-ph/9505060;
R. R. Caldwell, R. Dave and P. J. Steinhardt, Phys. Rev. Lett. 80, 1582 (1998) astro-ph/9708069;
I. Zlatev, L. M. Wang and P. J. Steinhardt, Phys. Rev. Lett. 82, 896 (1999) astro-ph/9807002.

[7] C. Armendariz-Picon, V. F. Mukhanov and P. J. Steinhardt, Phys. Rev. Lett. 85, 4438 (2000) astro-ph/0004134;
C. Armendariz-Picon, V. F. Mukhanov and P. J. Steinhardt, Phys. Rev. D 63, 103510 (2001) astro-ph/0006373.

[8] A. Sen, JHEP 0207, 065 (2002) hep-th/0203265.

[9] R. R. Caldwell, Phys. Lett. B 545, 23 (2002) astro-ph/9908168;
R. R. Caldwell, M. Kamionkowski and N. N. Weinberg, Phys. Rev. Lett. 91, 071301 (2003) astro-ph/0302506;
S. Nojiri and S. D. Odintsov, Phys. Lett., B 562, 147, (2003);
S. Nojiri and S. D. Odintsov, Phys. Lett., B 565, 1, (2003); M. R. Setare, Eur. Phys. J. C 50, 991, (2007).

[10] N. Arkani-Hamed, H. C. Cheng, M. A. Luty and S. Mukohyama, JHEP 0405, 074 (2004) [hep-th/0312099].

[11] F. Piazza and S. Tsujikawa, JCAP 0407, 004 (2004) [hep-th/0405054].

[12] B. Feng, X. L. Wang and X. M. Zhang, Phys. Lett. B 607, 35 (2005) [astro-ph/0404224]; Z. K. Guo, Y. S. Piao, X. M. Zhang and Y. Z. Zhang, Phys. Lett. B 608, 177 (2005) [astro-ph/0410654]; A. Anisimov, E. Babichev and A. Vikman, JCAP 0506, 006 (2005) [astro-ph/0504560]; M. R. Setare, Phys. Lett. B 641, 130, (2006); E. Elizalde, S. Nojiri, and S. D. Odintsov, Phys. Rev. D 70, 043539, (2004); S. Nojiri, S. D. Odintsov, and S. Tsujikawa, Phys. Rev. D 71, 063004, (2005); M. R. Setare, J. Sadeghi, and A. R. Amani, Phys. Lett. B 660, 299 (2008); M. R. Setare and E. N. Saridakis, Phys. Lett. B 668, 177 (2008) [arXiv:0802.2595 [hep-th]]; M. R. Setare and E. N. Saridakis, JCAP 09, 026 (2008) [arXiv:0809.0114 [hep-th]].

[13] L. Amendola, Phys. Rev. D 62, 043511 (2000) [astro-ph/9908023]; D. Comelli, M. Pietroni and A. Riotto, Phys. Lett. B 571, 115 (2003) [hep-ph/0302080]; M. Szydlowski, A. Kurek, and A. Krawiec Phys. Lett. B 642, 171, (2006) [astro-ph/0604327]; M. R. Setare, JCAP, 0701, 023, (2007); M. R. Setare, Elias. C. Vagenas, [arXiv:0704.2070 [hep-th]].

[14] C. Deffayet, G. R. Dvali and G. Gabadadze, Phys. Rev. D 65, 044023 (2002) [astro-ph/0105068]; V. Sahni and Y. Shtanov, JCAP 0311, 014 (2003) [astro-ph/0202346]; M. R. Setare, Phys. Lett. B 642, 421, (2006).

[15] A. Y. Kamenshchik, U. Moschella and V. Pasquier, Phys. Lett. B 511, 265 (2001) [gr-qc/0103004].

[16] R. Herrera, D. Pavon and W. Zimdahl, Gen. Rel. Grav. 36, 2161 (2004).

[17] A. Sen, JHEP 0204, 048 (2002); JHEP 0207, 065 (2002); Mod. Phys. Lett. A 17, 1797 (2002); arXiv: hep-th/0312153.

[18] A. Sen, JHEP 9910, 008 (1999); E. A. Bergshoeff, M. de Roo, T. C. de Wit, E. Eyras, S. Panda, JHEP 0005, 009 (2000); J. Kluson, Phys. Rev. D 62, 126003 (2000); D. Kutasov and V. Niarchos, Nucl. Phys. B 666, 56, (2003).

[19] A. Frolov, L. Kofman and A. Starobinsky, Phys. Lett. B545, 8, (2002).

[20] V. Gorini, A. Kamenshchik, U. Moschella and V. Pasquier, and A. Starobinsky, astro-ph/0504576.
[21] C. L. Bennet et al, astrophys. J. Suppl., 148, (2003) 1; D. N. Spergel, Astrophys. J. Suppl., 148, (2003), 175; K. Ichikawa et al, astro-ph/0605481

[22] Q. G. Huang and M. Li, JCAP, 0408, 013, (2004).

[23] M. Tegmark, et al. ApJ, 606, 702, (2004).

[24] D. Polarski, and A. Ranquet, Phys. Lett. B 627, 1, (2005); U. Franca, Phys. Lett. B 641, 351, (2006); K. Ichikawa and T. Takahashi, Phys. Rev. D 73, 083526, (2006); Y. Gong, A. Wang, Phys. Rev. D75, 043520, (2007); K. Ichikawa; T. Takahashi, JCAP 0702, 001, (2007); E. L. Wright, astro-ph/0701584; G. Zhao, et al., astro-ph/0612728.

[25] C. Clarkson, M. Cortes, B. A. Bassett, JCAP 0708, 011, (2007).

[26] W. Chakraborty and U. Debnath, arxiv: 0804.4801v1 [gr-qc].

[27] D. Pavon and B. Wang, “Le Chatelier-Braun principle in cosmological physics,” arXiv:0712.0565 [gr-qc].

[28] D. Pavon and W. Zimdahl, Phys. Lett. B 628, 206 (2005) arXiv:gr-qc/0505020.

[29] L. Amendola, G. Camargo Campos and R. Rosenfeld, Phys. Rev. D 75, 083506 (2007) arXiv:astro-ph/0610806;
Z. K. Guo, N. Ohta and S. Tsujikawa, Phys. Rev. D 76, 023508 (2007) arXiv:astro-ph/0702015.

[30] B. Wang, Y. Gong, E. Abdalla, Phys. Lett. B 624, 141, (2005);
B. Wang, C. Y. Lin and E. Abdalla, Phys. Lett. B 637, 357 (2006)
arXiv:hep-th/0509107;
K. Karwan, JCAP 0805, 011 (2008) arXiv:0801.1755 [astro-ph]].

[31] T. Padmanabhan, Phys. Rev. D66, 021301 (2002); J. S. Bagla, H. K. Jassal and T. Padmanabhan, Phys. Rev. D67, 063504 (2003); A. Feinstein, Phys. Rev. D66, 063511, (2002); L. R.W. Abramow and F. Finelli, Phys. Lett. B 575 (2003) 165; J. M. Aguirre-gabiria and R. Lazkoz, Phys. Rev. D 69, 123502 (2004); Z. K. Guo and Y. Z. Zhang, JCAP 0408, 010 (2004); M. R. Setare, Phys. Lett. B653, 116, (2007).

[32] O. Bertolami, F. Gil Pedro and M. Le Delliou, Phys. Lett. B 654, 165 (2007) arXiv:astro-ph/0703462;
M. Le Delliou, O. Bertolami and F. Gil Pedro, AIP Conf. Proc. 957, 421 (2007) arXiv:0709.2505 [astro-ph]].

[33] C. Feng, B. Wang, Y. Gong and R. K. Su, JCAP 0709, 005 (2007) arXiv:0706.4033 [astro-ph];
E. Abdalla, L. R. W. Abramow, L. J. Sodre and B. Wang, “Signature of the interaction between dark energy and dark matter in galaxy clusters,” arXiv:0710.1198 [astro-ph].