Tachyon as a Dark Energy Source

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It is demonstrated that dark energy, driven by tachyons, having non-minimal coupling with curvature and self-interacting inverse cubic potential, decays to cold dark matter in the late accelerated universe. It is found that this phenomenon yields a solution to “cosmic coincidence problem”. PACS nos.: 98.80 Cq, 95.35.+d.

Key Words : Tachyon, dark energy, dark matter and accelerated cosmic expansion.

The idea of tachyons is not new. It was proposed around 40 years back [1] and some cosmological models also were developed [2]. Later on, these superluminal particles were discarded for not being observed. At the turn
of the last century, it has re-attracted attention of physicists appearing as condensates in some of string theories. After a series of papers by Sen[3], once again these particles were drawn into the arena of cosmology[4]. For not being observed, tachyons too are considered as good candidates for dark energy (DE), apart from various DE models such as quintessence[5] and k-essence[6] models, where these fields violate “strong energy condition” (SEC). Recently, some other scalar field models for DE have appeared where “weak energy condition” (WEC) is violated[7,8].

In the recent literature, study on tachyon scalar field $\phi$ has been done with Born-Infeld lagrangian $-V(\phi)\sqrt{1 - g^{\mu \nu} \partial_\mu \phi \partial_\nu \phi}$ having minimal coupling with gravity. Later on, it was shown that this lagrangian can also be treated as generalization of a relativistic particle lagrangian [9]. Recently, another tachyon model, with minimal coupling, has been proposed with lagrangian $W(\phi)\sqrt{g^{\mu \nu} \partial_\mu \phi \partial_\nu \phi - 1}$ (with $W(\phi)$ real). Using this lagrangian, it is argued that tachyon scalars may be able to explore more physical situations than quintessence [10].

For a non-tachyonic scalar $\psi$, having non-minimal coupling with curvature, lagrangian is taken as $L^\psi = \sqrt{-g}[\frac{1}{2} g^{\mu \nu} \partial_\mu \psi \partial_\nu \psi - \frac{1}{2} \xi R \psi^2 - V(\psi)]$ (with $W(\phi)$ real). Using this lagrangian, it is argued that tachyon scalars may be able to explore more physical situations than quintessence [10].

In a similar way, it is reasonable to explore dynamics of tachyon scalar $\phi$ also, taking its non-minimal coupling with gravity, through the lagrangian

$$L^\phi = \sqrt{-g} \left[ -V(\phi)\sqrt{1 - g^{\mu \nu} \partial_\mu \phi \partial_\nu \phi + \xi R \phi^2} \right],$$

(1)
where $V(\phi)$ is the potential.

Non-minimal coupling of tachyon with gravity was also proposed by Piao et al [11] in a different manner, where a function of $\phi$ is coupled to Einstein-Hilbert lagrangian as

$$S = \int \! d^4x \sqrt{-g} \left[ \frac{f(\phi)R}{16\pi G} + V(\phi) \sqrt{1 + \alpha' g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi} \right]$$

Where $\alpha'$ gives the string mass scale.

Subject to the condition $1 - g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi >> \xi R\phi^2$, the lagrangian (1) looks like

$$L_\phi \simeq \sqrt{-g} \left[ -V(\phi) \sqrt{1 - g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi} - \frac{1}{2} \frac{\xi V(\phi)\phi^2 R}{\sqrt{1 - g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi}} \right],$$

which is similar to lagrangian of the action, taken by Piao et al with non-minimal coupling function $f(\phi) = -8\pi G \frac{\xi V(\phi)\phi^2}{\sqrt{1 - g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi}}$.

In what follows, investigations are made using the lagrangian (1) for the tachyon scalar $\phi$. In the case of minimal coupling with gravity, tachyons behave as dust in the late universe, as pressure for tachyon $p^\phi \to 0$, when $\dot{\phi} = \frac{d\phi}{dt} \to 1$. In the model with non-minimal coupling, taken here, $p^\phi$ does not vanish when $\dot{\phi} \to 1$. Moreover, equation of state parameter $w^\phi = p^\phi / \rho^\phi < -1/3$, (where $\rho^\phi$ is the tachyon energy density) which causes accelerated expansion of the universe predicted by recent experiments Ia supernova [12, 13] and WMAP (Wilkinson Microwave Anisotropy Probe) [14 -16].

It is found that DE density decreases with expansion of the universe arousing a question “Where is dark energy going?”. Recently, in a non-tachyonic case [17], it is proposed that there is no dark matter (DM) in
the beginning of the universe, but it is created due to decay of DE after the universe starts expanding. As a result, DE density decreases and DM density increases, in such a way that both become of the same order at the present age of the universe.

Here, it is demonstrated that, in the late universe, cold dark matter (CDM) is created due to decay of tachyon dark energy. It is found that \( r(t) = \rho_m(t)/\rho(t) \) (\( \rho_m(\rho) \) being CDM (DE) density) grows with time, but keeping itself less than unity. Thus, it provides a solution to “cosmic coincidence problem” CCP, which asks how DE and CDM densities are of the same order in the current universe [18]. This mechanism is different from earlier ones [5], in which DE density is supposed to be lower than the same for matter and radiation in the early universe, but become comparable to the latter in the current universe. Moreover, it is also different from the approach of Zimdahl et al. [19 - 21], where \( r \) is shown stable in late times. Natural units \((\hbar = c = 1)\) are used here.

The paper begins with Einstein’s field equations

\[
R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -8\pi G(T_{\mu\nu}^{\phi} + T_{\mu\nu}^{(m)}) \tag{2a}
\]

with the gravitational constant \( G = M_P^2(M_P = 10^{19} \text{ GeV} \text{ being the Planck mass}) \) and energy momentum tensor components for tachyons, given as

\[
T_{\mu\nu}^{\phi} = (\rho^\phi + p^\phi)u_\mu u_\nu - p^\phi g_{\mu\nu} \tag{2b}
\]

and

\[
T_{\mu\nu}^{(m)} = (\rho^{(m)} + p^{(m)})u_\mu u_\nu - p^{(m)} g_{\mu\nu}, \tag{2c}
\]

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where $\rho^\phi(\rho^m)$ and $p^\phi(p^m)$ are energy density and pressure for tachyon(matter) respectively. Here, matter is CDM, so $p^m = 0$. $u^\mu = (1, 0, 0, 0)$. For tachyonic perfect fluid $T^\phi_\mu = (\rho^\phi, -p^\phi, -p^\phi, -p^\phi)$ are given by

\[
T^\phi_\mu = -V(\phi)[1 - \nabla^\rho \phi \nabla_\rho \phi + \xi R\phi^2]^{-1/2} \times \left[ -\nabla_\mu \phi \nabla_\nu \phi + \xi R_{\mu\nu}\phi^2 \\
+ \xi(\nabla_\mu \nabla_\nu - g_{\mu\nu} \Box)\phi^2 - g_{\mu\nu}(1 - \nabla^\rho \phi \nabla_\rho \phi + \xi R\phi^2) \right]
\]

(3)
derived from the lagrangian (1). Here $\nabla_\mu$ stands for covariant derivative $R_{\mu\nu}$ are Ricci tensor components.

Field equations for $\phi$ are obtained as

\[
\Box \phi + \frac{2(\nabla^\mu \phi)(\nabla_\rho \phi)(\nabla^\rho \nabla_\mu \phi)}{2(1 - \nabla^\rho \phi \nabla_\rho \phi + \xi R\phi^2)} \cdot \frac{2\xi R\phi(\nabla^\rho \phi)(\nabla_\rho \phi) - \xi \phi^2 g^{\mu\nu}(\nabla_\mu R)(\nabla_\nu \phi)}{2(1 - \nabla^\rho \phi \nabla_\rho \phi + \xi R\phi^2)} \\
+ \xi R\phi + \frac{V'}{V}(1 + \xi R\phi^2) = 0,
\]

(4)
where $V'(\phi) = \frac{d}{d\phi} V(\phi)$ and

\[
\Box = \nabla^\rho \nabla_\rho = \frac{1}{\sqrt{-g}} \frac{\partial}{\partial x^\mu} (\sqrt{-g} g^{\mu\nu} \frac{\partial}{\partial x^\nu}).
\]

Data of Ia Supernova [12, 13] and WMAP [14, 15, 16] indicate that we live in a spatially flat accelerated universe such that $\ddot{a}/a > 0$ for the scale factor $a(t)$, given by the distance function

\[
dS^2 = dt^2 - a^2(t)[dx^2 + dy^2 + dz^2]
\]

(5)
representing a homogeneous model of the universe. Hence,
\[ \phi(x,t) = \phi(t). \] (6)

The action \( S \) shows that, in natural units, \( \phi \) has mass dimension equal to \(-1\) like time \( t \). So, on the basis of dimensional considerations, it is reasonable to take

\[ \phi(t) = At. \] (7)

where \( A \) is a dimensionless constant.

The potential is taken as

\[ V(\phi) = \sqrt{\frac{3}{8\pi G}} \phi^{-3}, \] (8)

as \( G \) gives a natural scale in gravity.

**For the case \( \xi \neq 0 \)**

Connecting eqs. (4) - (8), it is obtained that eq.(4) looks like

\[ 3AH - \frac{\xi A^3 t (2R + t\dot{R})}{2[1 - A^2 + 2\xi A^2 t^2 R]} + \xi AtR - \frac{3}{At}(1 + \xi A^2 t^2 R) = 0, \] (9)

where \( H = \frac{\dot{a}}{a} \) with \( \dot{a} = \frac{da}{dt} \).

Eq.(9) admits the power-law solution

\[ a(t) = a_i(t/t_i)^q \] (10)

provided that

\[ 24\xi q^2 A^2 - 3A^2(1 + 4\xi)q + 3 = 0. \] (11)
In eq.(10), \( t_i \) is the time, when decay of DE to CDM begins and \( a_i \) is the corresponding scale factor.

For the geometry, given by eq.(5), eqs.(3) yield energy density

\[
\rho^\phi = T_0^{(\phi)0} = V(\phi) \frac{[1 + 6\xi H \phi \dot{\phi} + 3\xi(\dot{H} + 3H^2)\phi^2]}{\sqrt{1 - \dot{\phi}^2 + 6\xi\phi^2(\dot{H} + 2H^2)}}
\]

(12a)

and isotropic pressure as

\[
p^\phi = -V(\phi) \frac{[1 - \dot{\phi}^2 + \xi(2\phi \ddot{\phi} + 2\dot{\phi}^2 + 6\xi H \phi \dot{\phi}) + \xi(5\dot{H} + 9H^2)\phi^2]}{\sqrt{1 - \dot{\phi}^2 + 6\xi\phi^2(\dot{H} + 2H^2)}}
\]

(12b)

Eqs.(12) show that, in minimal coupling case, \( \rho^\phi = V(\phi)/\sqrt{1 - \dot{\phi}^2} \) and \( p^\phi = -V(\phi)\sqrt{1 - \dot{\phi}^2} \) on taking \( \xi = 0 \) as obtained in refs.[3,4] for Sen’s model. It is interesting to see that, on taking non-minimal coupling of \( \phi \) with curvature (\( \xi \neq 0 \)), \( p^{(\phi)} \not\to 0 \), when \( \dot{\phi} \to 1 \), contrary to Sen’s model and Pio’s way of taking non-minimal coupling, where \( p^{(\phi)} \to 0 \), when \( \dot{\phi} \to 1 \).

Due to dominance of DE over matter, eqs.(2) yield

\[
\frac{R_1^1 - (1/2)R}{R_0^0 - (1/2)R} = \frac{-p^\phi}{\rho^\phi} = -w^\phi.
\]

(13)

Connecting eqs.(7), (12) and (13), it is obtained that

\[
\frac{3H^2 + 2\dot{H}}{3H^2} = \frac{[1 - \dot{\phi}^2 + \xi(2\phi \ddot{\phi} + 2\dot{\phi}^2 + 6\xi H \phi \dot{\phi}) + \xi(5\dot{H} + 9H^2)\phi^2]}{[1 + 6\xi H \phi \dot{\phi} + 3\xi(H + 3H^2)\phi^2]} = -w^\phi.
\]

(14)

Eqs.(7), (10) and (14) yield
\[
\frac{3q - 2}{3q} = 1 - A^2 + \xi(2 + q + 9q^2)A^2 \\
1 + 3\xi A^2(q + 2q^2) = -w^\phi. \quad (15)
\]

Eliminating \(A^2\) from eqs.(11) and (15), it is obtained that

\[
12\xi q^2 + 8\xi q - 16\xi + 1 = 0. \quad (16)
\]

Now subject to the condition \(1 - \dot{\phi}^2 + 6\xi(\dot{H} + 2H^2) = 1 - A^2 + 6\xi A^2(-q + 2q^2) > 0\) (to get \(\rho^\phi\) and \(p^\phi\) real), a set of solutions of eqs.(11) and (16) is obtained as

\[
q = \frac{5}{3}, \xi = -\frac{3}{92}, A = \sqrt{\frac{69}{125}} \text{ and } w^\phi = -0.6. \quad (17a, b, c, d)
\]

As mentioned above, tachyon scalar field is a probable source of dark energy. So, \(\rho^\phi\) represents DE density. Eqs.(7), (8), (10), (12) and (17) imply that

\[
\rho^\phi = \sqrt{\frac{3}{8\pi G}} (At)^{-3} \frac{[1 + 3\xi q(1 + 3q)A^2]}{\sqrt{1 - A^2 + 6\xi A^2(-q + 2q^2)}} \quad (18)
\]

Eq.(18) shows that DE density rolls down with growing time. Hence, it is reasonable to propose that DE decays to CDM [17]. With \(\rho^m\) as CDM density and \(Q(t)\) as loss(gain) term for DE(CDM), this phenomenon is given by coupled equations

\[
\dot{\rho}^\phi + 3H(\rho^\phi + p^\phi) = -Q(t) \quad (19a)
\]

and

\[
\dot{\rho}^m + 3H\rho^m = Q(t) \quad (19b)
\]
derived from the Bianchi identities

\[ [T^{\mu \nu(\phi)} + T^{\mu \nu(m)}]_{\mu} = 0. \]

From eq.(15),

\[ q = \frac{2}{3(1 + w^{\phi})}. \] (20)

Using the equation of state \( p^\phi = w^\phi \rho^\phi \) and eq.(20) in eq.(19a), it is obtained that

\[ Q(t) = \left( \frac{1.84}{A^3 \sqrt{8\pi G}} \right) t^{-4} \] (21)

As mentioned above, here, it is proposed that CDM is produced due to decay of DE, so \( \rho^{(m)}(t_i) = 0 \), where \( t_i \) is the epoch when creation of CDM begins.

Now eq.(19b) is integrated to

\[ \rho^m = \left( \frac{1.84}{3A^3(q - 1) \sqrt{8\pi G}} \right) t^{-3} \left[ 1 - \left( \frac{t_i}{t} \right)^{3(q-1)} \right] \] (22a)

using eqs.(10), (17),(21) and \( \rho^m(t_i) = 0 \).

Now,

\[ r(t) = \frac{\rho^m}{\rho^\phi} = 0.5 \left[ 1 - \left( \frac{t_i}{t} \right)^2 \right] \] (22b)

for \( q \) and \( \rho^\phi \) from eqs.(17 a) and (18) respectively. Current data of the universe \( \rho_{0}^m = 0.23 \rho_{cr,0} \) and \( \rho_{0}^\phi = 0.73 \rho_{cr,0} \) for the current universe(where \( \rho_{cr,0} = 3H_0^2/8\pi G, H_0 = h/t_0, t_0 = 13.7 \text{Gyr} \) being the present age and parameter \( h = 0.72 \pm 0.08 \)) and eq.(22b) yield
\[ t_i = 0.608t_0. \]  \hspace{1cm} (23)

Thus eqs.(22b) and (23) imply

\[ r(t) = 0.5 \left[ 1 - 0.37 \left( \frac{t_0}{t} \right)^2 \right] \]  \hspace{1cm} (24)

showing that \( 0 < r(t) < 1 \) for \( 0.608t_0 \leq t \). This result provides a possible solution to CCP in the accelerated universe.

**For the case \( \xi = 0 \)**

In this case, eqs.(12) and (13) yield

\[ \frac{2\dot{H}}{3H^2} = -\dot{\phi}^2 \]  \hspace{1cm} (25)

and eq.(4) looks like

\[ \frac{\ddot{\phi}}{1 - \phi^2} + 3H\dot{\phi} - \frac{3}{\phi} = 0 \]  \hspace{1cm} (26)

for \( V(\phi) \) given by eq.(8) \([3,4]\).

The condition, for real \( \rho^\phi \) and \( p^\phi \), reduces to

\[ \dot{\phi}^2 < 1. \]  \hspace{1cm} (27)

Now, for slow roll-over of \( \phi, \ddot{\phi} \ll 3H\dot{\phi} \), so eq.(26) is re-written as

\[ H\dot{\phi} = \phi^{-1}. \]  \hspace{1cm} (28)

Eqs.(25) and (28) yield

\[ H = \frac{4t_i^{3/2}}{3\phi_i^2}t^{-1/2} \]  \hspace{1cm} (29a)
and
\[ \phi = \phi_i \left( \frac{t}{t_i} \right)^{3/4}. \]  

(29b)

Eq.(29a) yields \( a(t) = a_0 \exp \left\{ \frac{8}{3} \frac{t^{3/2}}{\phi_i^2} t^{1/2} \right\} \) implying accelerated expansion. Using these solutions in eq.(19a), it is obtained that

\[ Q(t) = \left( \frac{3}{\phi} - \frac{9}{4t} \right) V(\phi) \]  

(30)

with \( \rho^\phi \simeq V(\phi) \).

Integration of eq.(19b) with \( Q(t) \), given by eq.(30), yields

\[ \rho^m \approx \frac{3}{4} \sqrt{\frac{3}{8\pi G}} \phi_i^{-2} t_i^{3/2} t^{-5/2}. \]  

(31)

Eqs.(8) and (29b) yield

\[ \rho^\phi \simeq V(\phi) = \sqrt{\frac{3}{8\pi G}} \phi_i^{-3} \left( t/t_i \right)^{-9/4}. \]  

(32)

Using the current data for \( \rho^\phi \), given above, in eq.(32), it is obtained that

\[ \phi^{-1} = \left( 0.73 h^2 \sqrt{\frac{3}{8\pi G}} \right)^{1/3} t_0^{1/12} t_i^{3/4}. \]  

(33)

Eqs.(31) - (33) yield

\[ \left( \rho^m/\rho^\phi \right)_{t=t_0} \approx \frac{3}{4} \left( 0.73 h^2 \sqrt{\frac{3}{8\pi G}} \right)^{-1/3} t_0^{-1/3} \approx 10^{-20} \]  

(34)

This result (for minimal coupling case) contradicts observational data for the current universe giving \( \left( \rho^m/\rho^\phi \right)_{t=t_0} \simeq 0.37 \).

Thus, it is obtained that if tachyon dark energy decays to cold dark matter, “coincidence problem” in the accelerated universe can be solved
when tachyon scalar has non-minimal coupling to gravity, given by $\xi \neq 0$. This result is obtained for the universe using inverse cubic potential for $\phi$ (tachyon scalar) and without dissipative term for matter. It is interesting to see that $\rho^m$ gradually increases and $\rho^\phi$ decreases in such a way that both are almost of the same order in the late universe.

But in the case of minimal coupling ($\xi = 0$), it is found that enough amount of CDM is not created through decay of DE to get $\rho^m$ and $\rho^\phi$ comparable. Here also, no dissipative term for matter is taken. So, for this case “coincidence problem” is not solved in the speeded-up universe. This is parallel to results of refs.[20,21], where it is shown that, for the minimal case, CCP can not be solved for the accelerated universe without taking dissipative effects of CDM.

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