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Accelerated Dilatonic-Brans-Dicke cyclic and non-singular universe from string theory

Ahmad Rami El-Nabulsi

Department of Nuclear Engineering, Cheju National University, Ara-dong 1, Jeju 690-756, South Korea; *nabulsiahmadrami@yahoo.fr*
Key Laboratory of Numerical Simulation of Sichuan Province, Neijiang 641112, China
College of Mathematics and Information Science, Neijiang Normal University, Neijiang 641112, China

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Abstract We discuss the late-time dynamics of a particular four-dimensional Brans-Dicke cosmology with a dilaton field motivated by string theories (solitonic p-branes or D-branes) in which the dilaton field and the scale factor of the flat, homogeneous spacetime are correlated. We examine the late-time-evolution of the equations of motion where various attractive consequences are revealed and discussed in some detail.

Key words: cosmology: theory — cosmological parameters

1 INTRODUCTION

Dark energy and its associated cosmic acceleration after a long period of deceleration represent two serious problems in modern cosmology. These data are inferred from the observations of type Ia supernovae, cosmic microwave background (CMB) anisotropies, the large-scale galaxy structures of the universe and Sachs-Wolfe effects (Riess et al. 1998, 2004; Perlmutter et al. 1999; Schmidt et al. 1998; Steinhardt et al. 1999; Persic et al. 1996; Alcaniz 2004; de Bernardis et al. 2000; Sahni & Starobinsky 2000; Peebles & Ratra 2003; Padmanabhan 2005; Caldwell 2002; Starobinsky 2000; Caldwell et al. 2003). A possible source of the late-time acceleration is given by vacuum energy or the cosmological constant with a constant equation of state, or a variant of it, known as quintessence (de Bernardis et al. 2000). Several plausible cosmological scenarios have also been proposed to explain these problems within the context of modified theories of scalar-tensor gravity such as K-essence (Chiba et al. 2000; Chiba 2002; Armendariz-Picon et al. 2000, 2001), Chaplygin gas (Kamenshchik et al. 2001; Bento et al. 2002, 2004; Gorini et al. 2003; Alam et al. 2003; Bertolami et al. 2004), the generalized Chaplygin gas model (Zhu 2004; Kamenshchik et al. 2001; Bento et al. 2002), holographic dark energy (Setare & Saridakis 2008a,b; El-Nabulsi 2010c) and so on. These models are appealing since they can offer a possible solution to the cosmic coincidence problem.

A successful dark energy theory may be derived from either the modified gravity approach/deformed general relativity (MGA/DGR) or from string and M-theory (superstring). String theory is currently believed to be the most promising candidate to explain quantum gravity and hence one naturally expects that many problems in general relativity (GR), such as the initial singularity problem, may be solved (Maroto & Shapiro 1997; Antoniadis et al. 1994; Bento & Bertolami 1996; Maeda & Ohta 2005; Easther & Maeda 1996; Gasperini et al. 2002; Piazza & Tsujikawa 2004;

Calcagni et al. 2005; Srivastava 2008; Nojiri & Odintsov 2006a, 2007; Nojiri et al. 2005a,b, 2006; Bamba et al. 2007). It is noteworthy that the MGA/DGR is reduced within a certain limit to the standard GR. The MGA/DGR is enormously attractive in applications of the late accelerating universe and dark energy since it presents a very natural unification of early-time inflation and late-time acceleration. Furthermore, some cosmological effects (such as galaxy rotation curves) may be explained in terms of the MGA/DGR. The Brans-Dicke (BD) theory belongs to a class of the MGA/DGR that allows variable gravity coupling, however it is also motivated by string theory. In recent years, the study of BD cosmologies in four and extra dimensions has attracted much attention since the theory succeeded in elucidating the main part of significant features describing dynamics of the cosmos, mainly during the late time dynamical epoch. Despite the fact that BD cosmology continues with an irrelevant correction to the matter density constituent of the Friedmann equations and the intricacies of the decelerating expansion phase of the universe, it was realized that the best part of the cosmological BD models offers an insight into many significant elements of the dynamical evolution of the universe. It is noteworthy that the low-energy theory of the fundamental string gives the BD theory as a particular case, with a fine-tuned deformation parameter $\omega = -1$. In the high-curvature region, the coupling is also big. The slowing down of the inflationary rate and the end of the fast expansion rate due to bubble nucleation renders the BD theory an appealing candidate for many cosmological problems (El-Nabulsi 2010a, 2008, 2010b,d,e,g; Brans & Dicke 1961; Veneziano 1996). However, one possible way to deal with a successful dark energy theory is to implement in the theory a dynamical dilatonic field inspired by string theories, i.e. solitonic p-branes or D-branes (Park & Sin 1998, 1999; Lee & Sin 1998).

In this paper, we shall investigate a cosmological model based on the effective action of the dilaton field in the presence of a matter source term, in which the perfect fluid does not couple to the dilaton like the matter in the Ramond-Ramond sector of string theory. We keep the dilatonic BD parameter ω arbitrary so that the effective action includes a wide variety of theories. It is worth mentioning that solitonic p-brane gas treated as perfect fluid-type matter in a BD theory was recently explored for two independent cases: the first case corresponds to the case where the perfect fluid is not coupled to the dilaton; whereas, in the second case, the coupling was taken into account. In our approach, we will conjecture that the dilaton field ϕ is related to the scale factor of the four-dimensional flat, homogeneous spacetime through a certain power-law. In this work, we will take the free parameter $\omega = 1$ instead of the usual $\omega = -1$ that appears as previously stated in low energy string theory. Their structure follows from the compactification scheme aspect. If, for instance, one of the moduli fields has a flat direction along the dilaton, one might expect therefore to have $\omega \neq -1$.

2 SETUP: ACTION AND EQUATIONS OF MOTION

The action of the gravity theory that will be described in this paper in $D = 3+1$ dimensions is (Park & Sin 1999)

$$S_4 = \int d^4x\sqrt{-g}\left(\mathrm{e}^{-\phi}\left[R - \omega\partial_\mu\phi\partial^\mu\phi\right] + L_{\mathrm{matter}}\right), \tag{1}$$

where R is the scalar curvature, ϕ is the dilaton scalar field, g is the metric and L_{matter} is the matter Lagrangian. Despite the fact that this action may not be derived from string theory, it may be meaningful in its own right to explore its cosmological implications. Equation (1) indicates that Newton's constant is not a fixed quantity but rather a dynamical one determined by the dilaton field ϕ by $G \propto \mathrm{e}^{\phi}$.

The field equation which follows from the action (1) is

$$\begin{aligned} R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{1}{2}\mathrm{e}^{\phi}T_{\mu\nu} + \omega\left[\partial_\mu\phi\partial_\nu\phi - \frac{1}{2}g_{\mu\nu}(\partial\phi)^2\right] \\ + \left[-\partial_\mu\partial_\nu\phi + \partial_\mu\phi\partial_\nu\phi + g_{\mu\nu}\partial_\mu\partial^\mu\phi - g_{\mu\nu}(\partial\phi)^2\right], \end{aligned} \tag{2}$$

$$R - 2\omega\partial_\mu\partial^\mu\phi + \omega(\partial\phi)^2 = 0, \tag{3}$$

where $T_{\mu\nu} = pg_{\mu\nu} + (p+\rho)u_\mu u_\nu$ is the stress energy-momentum tensor. Here p and ρ are respectively the pressure and density of the perfect fluid and u_μ is the four velocity of the fluid rest frame. For a flat, homogeneous and isotropic background, the metric we adopt in our theory corresponds to a flat, homogeneous spacetime and can be written as

$$ds_4^2 = -dt^2 + \exp[2r(t)]\sum_{i=1}^{3} dx^i dx^i. \tag{4}$$

The $(0,0)$ component in the action has the form

$$-6\dot{r}^2 + 6\dot{r}\dot{\phi} + \omega\dot{\phi}^2 + \rho e^{\phi} = 0, \tag{5}$$

$$4\ddot{r} + 6\dot{\phi}^2 - 2\ddot{\phi} + (\omega+2)\dot{\phi}^2 - 4\dot{r}\dot{\phi} + pe^{\phi} = 0, \tag{6}$$

$$6\ddot{r} + 12\dot{r}^2 + 2\omega\dot{\phi}^2 + 6\omega\dot{r}\dot{\phi} = 0. \tag{7}$$

In this paper, we follow the arguments of Wang et al. (2010) and Arias et al. (2002), and we express the Hubble parameter as a function of the scalar field and its time-derivative and not of the time, i.e. $H = \dot{a}/a = \dot{r} = \epsilon + \delta\dot{\phi}, (\epsilon, \delta)$ are real variables. This equation represents the basic postulation of this paper. The motivations to introduce such an ansatz are the following:

(1) This ansatz may be constructed by an implicit symmetry of the field equations (Chimento 1998) and has been used as well in Aguirregabiria & Chimento (1996) to obtain 4d Poincare invariant solutions in thick brane contexts.
(2) Accurate solutions of the phantom dark energy cosmological model were also obtained using the same assumption with $(\epsilon = 0, \delta < 0)$ (Chimento et al. 1998, 1999; Ford 1987; Dev et al. 2001).
(3) It is noteworthy that in most of the inflationary cosmological models the Hubble parameter is proportional to the time-derivative of the scalar field.
(4) The authors speculate that this ansatz can cause the energy density and the Hubble parameter to oscillate, yielding a cyclic scenario. We will show the reader that the Hubble parameter will cross the constant ϵ cyclicly, which means that the Universe will alternately experience an expanding and a contracting phase.

We will show that this relation will yield motivating outcomes and solutions which are consistent with astrophysical observations.

3 COSMOLOGICAL SOLUTIONS

We can now write Equations (5)–(7) as an explicit function of the cosmic time

$$\rho = [6(\epsilon + \delta\dot{\phi})^2 - 6(\epsilon + \delta\dot{\phi})\dot{\phi} - \omega\dot{\phi}^2]e^{-\phi}, \tag{8}$$

$$p = \left[-4\delta\ddot{\phi} - 6\dot{\phi}^2 + 2\ddot{\phi} - (\omega+2)\dot{\phi}^2 + 4(\epsilon + \delta\dot{\phi})\dot{\phi}\right] e^{-\phi}, \tag{9}$$

$$6\delta\ddot{\phi} + \dot{\phi}^2\left(12\delta^2 + 2\omega + 6\omega\delta\right) + 6\left(\omega + 4\delta\right)\epsilon\dot{\phi} + 12\epsilon^2 = 0. \tag{10}$$

One possible and realistic class of solutions is obtained for $\omega = -4\delta = 1$ and therefore the solution of Equation (10) is given by

$$\phi(t) = \phi_0 - \frac{6}{35}\log\left[\cos\left(2\sqrt{\frac{35}{3}}\epsilon t\right)\right], \tag{11}$$

where $\phi_0 = \phi(t = 0)$ is the value of the scalar field at the beginning of the inflation epoch. Accordingly, the Hubble parameter and the scale factor vary respectively as

$$H = \dot{r} = \epsilon - \frac{3}{35}\sqrt{\frac{35}{3}}\epsilon \tan\left(2\sqrt{\frac{35}{3}}\epsilon t\right), \tag{12}$$

$$a(t) = a(0)\cos^{3/70}\left(2\sqrt{\frac{35}{3}}\epsilon t\right)\mathrm{e}^{\epsilon t}. \tag{13}$$

Here $a_0 = a(t = 0)$ is the value of the scale factor at the beginning of the inflation epoch. Having the scale factor oscillating and the universe alternately expanding and contracting may solve the big-bang singularity and coincidence problem. For this special case, the density and pressure of the perfect fluid vary respectively as

$$\rho(t) = 6\epsilon^2\mathrm{e}^{-\phi_0}\left[1 - \frac{18}{35}\sqrt{\frac{35}{3}}\tan\left(2\sqrt{\frac{35}{3}}\epsilon t\right) + \frac{7}{35}\tan^2\left(2\sqrt{\frac{35}{3}}\epsilon t\right)\right]\cos^{6/35}\left(2\sqrt{\frac{35}{3}}\epsilon t\right), \tag{14}$$

and

$$p(t) = \epsilon^2\mathrm{e}^{-\phi_0}\left[24 - \frac{24}{5}\tan^2\left(2\sqrt{\frac{35}{3}}\epsilon t\right) + \frac{48}{35}\sqrt{\frac{35}{3}}\tan\left(2\sqrt{\frac{35}{3}}\epsilon t\right)\right]\cos^{6/35}\left(2\sqrt{\frac{35}{3}}\epsilon t\right). \tag{15}$$

Since the universe contains a perfect fluid with a barotropic equation of state $p = \gamma\rho$, where γ is the equation of state parameter (EoSP), the conservation equation $\nabla_\mu T^{\mu\nu} = 0$ easily yields $\dot{\rho} + 3\dot{r}(p + \rho) = 0$ or

$$\begin{aligned}\gamma(t) = {} & -1 - \frac{2}{105}\sqrt{\frac{35}{3}} \\ & \frac{14\tan\left(2\sqrt{\frac{35}{3}}\epsilon t\right) - 18\sqrt{\frac{35}{3}}}{\left[\epsilon - \frac{3}{35}\sqrt{\frac{35}{3}}\epsilon\tan\left(2\sqrt{\frac{35}{3}}\epsilon t\right)\right]\left[1 - \frac{18}{35}\sqrt{\frac{35}{3}}\tan\left(2\sqrt{\frac{35}{3}}\epsilon t\right) + \frac{7}{35}\tan^2\left(2\sqrt{\frac{35}{3}}\epsilon t\right)\right]\cos^2\left(2\sqrt{\frac{35}{3}}\epsilon t\right)} \\ & + \frac{3}{35}\sqrt{\frac{35}{3}}\frac{\tan\left(2\sqrt{\frac{35}{3}}\epsilon t\right)}{\epsilon - \frac{3}{35}\sqrt{\frac{35}{3}}\epsilon\tan\left(2\sqrt{\frac{35}{3}}\epsilon t\right)}.\end{aligned} \tag{16}$$

For illustrative purposes, we choose $\epsilon = 1$.

The scale factor reaches the minimum of zero at $t = 5\pi(4n - 1)/68$ and $t = 5\pi(4n + 1)/68$, where $n \in \mathrm{Z}$, and the universe alternatively switches between expanding and contracting phases. The minimum points are the bouncing points. This behavior is repeated periodically due to the oscillatory nature of cosmic expansion. However, one important fact here is that the universe is also accelerated in time during the repeated cycles. This model can be regarded as an oscillating accelerated universe where the oscillation can be regarded as the result of the existence of a periodic dilaton field and the phenomenological law $H = \dot{a}/a = \dot{r} = \epsilon + \delta\dot{\phi}$, where (ϵ, δ) are real variables. In our arguments, the universe may cross the phantom barrier that corresponds to the EoSP $\gamma < -1$ and, besides, the universe is free from the initial singularity. The Hubble parameter presents a periodic behavior such that both early- and late-time accelerations are unified under the same mechanism.

The effective gravitational coupling constant $G \propto \mathrm{e}^{\phi}$ varies as

$$G = G_0\cos^{-6/35}\left(2\sqrt{\frac{35}{3}}\epsilon t\right), \tag{17}$$

where $G_0 = G(t = 0)$ is the value of the effective gravitational coupling constant at the beginning of the inflation epoch.

Despite the difficulties that seem to appear when confronting the predictions of an oscillating effective G model with other experimental data, an oscillating G is not ruled out from theory. Crittenden and Steinhardt argued that the nucleosynthesis constraint is so stringent that it practically rules out the oscillating G model unless we assume a "fine-tuning" within the oscillations of the scalar field (Crittenden & Steinhardt 1992; Salgado et al. 1996). It is noteworthy that the cosmological models based on non-minimal coupling (NMC) fields (Broadhurst et al. 1990; González et al. 2001, and references therein) and the periodic functional approach (El-Nabulsi 2010f) predict an oscillatory effective gravitational coupling constant. In the NMC theories, the effective gravitational coupling constant oscillates in time due to a contribution to it derived from the expectation value of the scalar field oscillating consistently in cosmic time in the bottom of its effective scalar field potential. This reasonable solution was proved to offer a practical solution that is well-matched to the most significant cosmological bounds of the Friedman-Robertson-Walker model and at the same time provides a reasonable explanation for the galactic periodicity discovered by Broadhurst et al. (El-Nabulsi 2010f). In addition, an occurrence of an oscillating universe is obtained using an inhomogeneous equation of state for dark energy fluid (Sáez-Gómez 2009). Cyclic and oscillating cosmologies arise as well in string theory and modified gravity (El-Nabulsi 2009; Cai & Saridakis 2011; Steinhardt & Turok 2002; Khoury et al. 2001, 2002a,b, 2004; Buchbinder et al. 2007; Nojiri & Odintsov 2006b; Yang & Wang 2005).

Another interesting case is related to the case $\omega = -1$ that appears in the low energy string theory for dilaton and graviton in the spectrum (Lidsey 1995; Lidsey et al. 2000; Dąbrowski 2001, 2002). Instead of choosing $\omega = -4\delta = 1$, we now choose $12\delta^2 + 2\omega + 6\omega\delta = 0$, i.e. $\delta = -0.22$ or $\delta = +0.72$. Accordingly, the differential Equation (10) takes the following form.

$$\ddot{\phi} + \frac{(4\delta - 1)\,\epsilon}{\delta}\dot{\phi} + \frac{2\epsilon^2}{\delta} = 0, \tag{18}$$

and the solution is given by

$$\phi(t) = -\frac{2\epsilon}{4\delta - 1}t + \frac{\delta}{(4\delta - 1)\,\epsilon}\left[1 - \mathrm{e}^{-\frac{(4\delta-1)\epsilon}{\delta}t}\right] + \phi(0). \tag{19}$$

Accordingly, the Hubble parameter, the scale factor, the gravitational coupling constant, the energy density, the energy pressure and the equation of state parameter vary respectively as

$$H = \frac{\dot{a}}{a} = \epsilon + \delta\left[-\frac{2\epsilon}{4\delta - 1} - \mathrm{e}^{-\frac{(4\delta-1)\epsilon}{\delta}t}\right], \tag{20}$$

$$a(t) = a(0)\exp\left\{\epsilon\frac{2\delta - 1}{4\delta - 1}t + \frac{\delta^2}{(4\delta - 1)\,\epsilon}\left[1 - \mathrm{e}^{-\frac{(4\delta-1)\epsilon}{\delta}t}\right]\right\}, \tag{21}$$

$$G \propto \mathrm{e}^{\phi} = \exp\left\{-\frac{2\epsilon}{4\delta - 1}t + \frac{\delta}{(4\delta - 1)\,\epsilon}\left[1 - \mathrm{e}^{-\frac{(4\delta-1)\epsilon}{\delta}t}\right] + \phi(0)\right\}, \tag{22}$$

$$\begin{aligned}\rho \;=\; & \mathrm{e}^{-\phi_0}\left\{(2 - 3\delta)\left[\frac{2\epsilon}{4\delta - 1} + \mathrm{e}^{-\frac{(4\delta-1)\epsilon}{\delta}t}\right]^2 - 6\epsilon(2\delta - 1)\left[\frac{2\epsilon}{4\delta - 1} + \mathrm{e}^{-\frac{(4\delta-1)\epsilon}{\delta}t}\right] + 6\epsilon^2\right\} \\ & \times\; \exp\left\{\frac{2\epsilon}{4\delta - 1}t - \frac{\delta}{(4\delta - 1)\,\epsilon}\left[1 - \mathrm{e}^{-\frac{(4\delta-1)\epsilon}{\delta}t}\right]\right\},\end{aligned} \tag{23}$$

$$p = e^{-\phi_0}\left\{\frac{2(1-2\delta)(4\delta-1)\epsilon}{\delta}e^{-\frac{(4\delta-1)\epsilon}{\delta}t} + (4\delta-7)\left[\frac{2\epsilon}{4\delta-1} + e^{-\frac{(4\delta-1)\epsilon}{\delta}t}\right]^2 - 4\epsilon\left[\frac{2\epsilon}{4\delta-1} + e^{-\frac{(4\delta-1)\epsilon}{\delta}t}\right]\right\} \times \exp\left\{\frac{2\epsilon}{4\delta-1}t - \frac{\delta}{(4\delta-1)\epsilon}\left[1 - e^{-\frac{(4\delta-1)\epsilon}{\delta}t}\right]\right\}, \quad (24)$$

and

$$\gamma(t) = \frac{\frac{2(1-2\delta)(4\delta-1)\epsilon}{\delta}e^{-\frac{(4\delta-1)\epsilon}{\delta}t} + (4\delta-7)\left[\frac{2\epsilon}{4\delta-1} + e^{-\frac{(4\delta-1)\epsilon}{\delta}t}\right]^2 - 4\epsilon\left[\frac{2\epsilon}{4\delta-1} + e^{-\frac{(4\delta-1)\epsilon}{\delta}t}\right]}{(2-3\delta)\left[\frac{2\epsilon}{4\delta-1} + e^{-\frac{(4\delta-1)\epsilon}{\delta}t}\right]^2 - 6\epsilon(2\delta-1)\left[\frac{2\epsilon}{4\delta-1} + e^{-\frac{(4\delta-1)\epsilon}{\delta}t}\right] + 6\epsilon^2}. \quad (25)$$

The universe for this special case is non-singular and non-cyclic. At very large time, the EoSP goes from $\epsilon > 0$ to

$$\gamma(t) = \frac{(4\delta-7)\left(\frac{2\epsilon}{4\delta-1}\right)^2 - 4\epsilon\left(\frac{2\epsilon}{4\delta-1}\right)}{(2-3\delta)\left(\frac{2\epsilon}{4\delta-1}\right)^2 - 6\epsilon(2\delta-1)\left(\frac{2\epsilon}{4\delta-1}\right) + 6\epsilon^2}, \quad (26)$$

and more particularly for $\epsilon = 1$, we get $\gamma(t \to \infty) = -0.33$ for $\delta = -0.22$ and $\gamma(t \to \infty) = -2.06$ for $\delta = 0.72$. The first case corresponds to dark energy dominance whereas the second case corresponds to phantom energy dominance.

It is obvious that for $\delta = -0.22$, the universe accelerates more in time than in the case of $\delta = 0.72$. The gravitational coupling constant in turn varies as

$$G \propto e^{\phi} = \exp\left\{1.06t + 0.11\left(1 - e^{-8.5t}\right) + \phi(0)\right\}, \quad (27)$$

for $\delta = -0.22$ and

$$G \propto e^{\phi} = \exp\left\{-1.06t + 0.38\left(1 - e^{-2.6t}\right) + \phi(0)\right\}, \quad (28)$$

for $\delta = 0.72$.

As we expect, based on recent observational limits, the universal expansion is accelerating in time, so the value $\delta = -0.22$ is more appropriate than $\delta = 0.72$.

In this scenario, since the universe is accelerating exponentially in time, its energy density decays to a certain negative value rather than tends to zero at a very large time; the cosmos is dominated by dark energy and the effective gravitational coupling constant is increasing with time.

4 CONCLUSIONS AND PERSPECTIVES

In conclusion, the accelerated expansion of the universe, the singularity problem and cosmological dark energy are perhaps the most important challenges facing high energy physics and astronomy, and all attempts at understanding their behavior have thus far been unsuccessful. The two models discussed here are simple, however, their phenomenological consequences should be further investigated and compared with other cosmological models (El-Nabulsi 2011; Acquaviva & Verde 2007; Wu et al. 2010; Wu & Chen 2010). Nevertheless, it was observed that the dilaton field and the phenomenological law $H = \dot{a}/a = \dot{r} = \epsilon + \delta\dot{\phi}$, where (ϵ, δ) are real variables, may drastically change standard cosmology. One more future research direction should be mentioned which corresponds to the stability problem.

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