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Dark energy in five-dimensional Brans-Dicke cosmology with dimensional reduction

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Abstract We explore a 5D Brans-Dicke scalar cosmology by conjecturing that the four-dimensional Hubble parameter varies as $H = \varepsilon\phi^s$, $\varepsilon \in \mathbb{R}$ and s is some unknown power index and that the extra-dimensions compactify as the visible dimensions expand as $b(t) \approx a^x(t)$, $x \in \mathbb{R}^-$. We mainly discuss the case $x = -1$. For critical values of ε close to unity, it was observed that the acceleration of the universe occurs at redshift close to $z = 0.8$ which indicates that in our model, accelerated expansion of the universe began only recently. Several interesting points are revealed and discussed in some detail.

Key words: Brans-Dicke cosmology — dark energy

1 INTRODUCTION

Recent astronomical observations with great precision and accuracy of the Cosmic Microwave Background (CMB) Anisotropy from WMAP (Wilkinson Microwave Anisotropy Probe), the Hubble diagram of type Ia Supernovae (SNe Ia) and the Lyα forest argue that our universe is governed by a nonzero cosmological constant with $\Omega_\Lambda \approx 0.72$ and has undergone a phase of accelerated expansion tending to a flat de-Sitter space-time as predicted by inflation theory with $\Omega_{\rm m} \approx 0.28$ (Riess et al. 1998; Cunha 2009; Perlmutter et al. 1999; Schmidt et al. 1998; Steinhardt et al. 1999; Persic et al. 1996; Riess et al. 2004; Alcaniz 2004). These findings are in accordance with results of BOOMERANG experiments (Ostriker & Steinhardt 1995) and are in agreement with a number of independent observations, especially concerning the mass of clusters. In other words, up to 70% of the total density consists of an unknown vacuum energy density or its effective equivalent and weakly interacting dark matter. The observed ordinary matter is on the order of 1% of the critical value and thus there exists a great quantity of dark matter (Riess et al. 2004). Dark energy and dark matter are in reality very troubling problems and one expects to derive new physics for a realistic explanation. To enlighten the dark energy issue, several phenomenological candidates and cosmological scenarios have been postulated and confronted with observations: the ΛCDM scenario (Peebles & Ratra 2003), K-essence (Armendariz-Picon et al. 2001), viscous fluid (Fabris et al. 2006a,b), Chaplygin gas (Fabris et al. 2002; Kamenshchik et al. 2001), Generalized Chaplygin gas model which mimics both dark matter and dark energy (Bilić et al. 2002; Bento et al. 2002), varying neutrino mass (Brookfield et al. 2006; Fardon et al. 2004), holographic dark energy (Setare & Saridakis 2008b,a), quintom cosmology (Guo et al. 2005; Xia et al. 2005; Sadeghi et al. 2008; Zhao et al. 2007) and so on. Most of these theories faced many difficulties like the cosmic coincidence problem and the initial singularity problem. However, regardless of their motivating consequences, the accelerated expansion of the universe and the nature of dark energy and dark matter cannot be explained by the standard model of particle physics and classical general relativity, i.e. a modified gravity theory is required.

The Brans-Dicke theory is a generic modification of Einstein's general relativity theory allowing variable gravity coupling (Brans & Dicke 1961). It is noteworthy that the low energy limit of the string theory contains the Brans-Dicke theory with a fine tuned deformation parameter $\omega = -1$ (Veneziano 1996). Generalized Brans-Dicke theory with a time-dependent parameter (sometimes referred to as graviton-dilaton or scalar-tensor theory) appears as well in supergravity and Kaluza-Klein theories (Nordtvedt 1970; Bergmann 1968; Wagoner 1970; Sahoo & Singh 2002). Nevertheless, Brans-Dicke cosmological theory with a constant ω is also an attractive theory in its own right since it also receives strong support from string and Kaluza-Klein theories (Kalyana Rama & Ghosh 1996; Kalyana Rama 1996). It was recently argued that the Brans-Dicke cosmology with a standard kinetic term for the scalar field but no mass term has the same radiation dominated solution as standard Einstein cosmology without a cosmological constant (Arik & Amon Susam 2010). Also, it was observed that Brans-Dicke can make a correction to the matter density component of the equation (Barrow 1993; Arik et al. 2008). Besides, the Brans-Dicke theory is successful for solving many problems in cosmology and all important features of the cosmic evolution of the universe such as inflation (Mathiazhagan & Johri 1984), early and late time behavior of the universe (La & Steinhardt 1989), structure formation (Bertolami & Martins 2000) and the coincidence problem (Banerjee & Pavón 2001; Sen & Seshadri 2003) could be explained successfully in the Brans-Dicke formalism. Apart from the above, Einstein's general relativity is recovered when $\omega \rightarrow \infty$; from timing experiments using the Viking space probe (Reasenberg et al. 1979), one finds $\omega > 40000$. This constraint ruled out various cases of extended inflation (Weinberg 1989; La et al. 1989). For a large value of the ω-parameter, the Brans-Dicke theory gives the right amount of inflation and early and late time behaviors, whereas small and negative values explain cosmic accelerated expansion, structure formation and the coincidence problem.

In this paper, we discuss our model within the structure of a five-dimensional homogeneous and isotropic space described by the flat metric, with $a(t)$ being the scale factor of the 3-space and $b(t)$ is the scale factor of the fifth dimension in a simple Brans-Dicke scalar field cosmological model. This class of generalized models is appealing for many reasons. It naturally appears in higher-dimensional theories like supergravity, Kaluza-Klein and in all the recognized effective string actions (Serna & Alimi 1996; Damour & Nordtvedt 1993; Kalyana Rama & Ghosh 1996; Kalyana Rama 1996; Nordtvedt 1970). In fact, higher-dimensional theories were reintroduced in physics to exploit the special properties that supergravity and superstring theories possess for particular values of spacetime dimensions (Randall & Sundrum 1999; Rubakov 2001; Hewett & Spiropulu 2002). Our four-dimensional universe is actually described by a general relativistic theory in a spacetime with one or more extra compactified dimensions. These higher-dimensional theories are now an active field of research in both general relativity and high energy physics in their attempts to unify gravity with all forces of nature. However, in the present epoch, these extra-dimensions are not observed presumably because they shrink in time to a tiny unobservably small length (Bhowmik & Rajput 2003; Bahrehbakhsh et al. 2010). Throughout this work, we conjecture that the four-dimensional Hubble parameter $H = \dot{a}/a$ varies as $H = H(\phi) = \varepsilon\phi^s$ where ε is a positive parameter and s is some pending power index. This ansatz is in reality motivated from various non-minimal coupling aspects of chaotic inflationary scenarios (Chen et al. 2008; Wang & Yang 2005). Moreover, we conjecture that the extra-dimensions compactify as the visible dimensions expand as $b(t) \approx a^x(t), x \in \mathbb{R}^-$ (El-Nabulsi 2009a,b).

2 ACTION OF THE THEORY AND EQUATIONS OF MOTION

The action of the theory is given by (in units $\hbar = c = 8\pi G = 1$)

$$S[g_{ab}, \phi] = \frac{1}{2}\int d^5x\sqrt{-g^{(5)}}(\phi^{(5)}R - \frac{\omega}{\phi}g^{ab}\phi_{,a}\phi_{,b}) + \int d^5x\sqrt{-g^{(5)}}L_{\mathrm{matter}}\,, \quad (1)$$

where L_{matter} is the Lagrangian of the ordinary matter, ${}^{(5)}R$ is the 5D Ricci scalar curvature, $g^{(5)}$ is the 5D scalar metric and $a, b = 0, 1, 2, 3, 4$. Varying the action (1) with respect to the metric and scalar field yields the following equations of motion

$$R_{ab} - \frac{1}{2}g_{ab}R - \frac{\omega}{\phi^2}\Big(\phi_{,a}\phi_{,b} - \frac{1}{2}g_{ab}\phi^{,c}\phi_{,c}\Big) - \frac{1}{\phi}\Big(\phi_{;ab} - g_{ab}{}^{(5)}\Box\phi\Big) = \frac{1}{\phi}{}^{(5)}T_{ab}, \quad (2)$$

$${}^{(5)}\Box\phi = \frac{1}{4+3\omega}{}^{(5)}T, \quad (3)$$

where ${}^{(5)}\Box$ is the five-dimensional d'Alembertian operator, ${}^{(5)}T_{ab}$ is the 5D energy-momentum tensor and ${}^{(5)}T = {}^{(5)}T_c^c$. The resulting equations of motion for the 5D metric are

$$(1+x)H^2 + (1+x)H\frac{\dot{\phi}}{\phi} - \frac{\omega}{6}\frac{\dot{\phi}^2}{\phi^2} = \frac{\rho}{3\phi}, \quad (4)$$

$$(2+x)(\dot{H} + H^2) + (x^2+x+1)H^2 + \frac{\omega}{2}\frac{\dot{\phi}^2}{\phi^2} + (2+x)H\frac{\dot{\phi}}{\phi} + \frac{\ddot{\phi}}{\phi} = -\frac{p}{\phi}, \quad (5)$$

$$\ddot{\phi} + (3+x)H\dot{\phi} = \frac{\rho - 3p}{4+3\omega}. \quad (6)$$

In addition, we assume that the stress energy tensor takes the form of a perfect fluid, i.e. $T_{ab} = \mathrm{diag}(\rho, p, p, p, p)$ in an orthonormal frame. Adopting the equation of state $p = (\gamma - 1)\rho$, γ is a constant, and p and ρ are respectively the fluid pressure and density. This satisfies the conservation equation $\dot{\rho} + (3H + \dot{b}\big/b)\gamma\rho = 0$ or $\dot{\rho} + (3+x)H\gamma\rho = 0$. Now we can write the three previous equations as

$$(1+x)H^2 + (1+x)H\frac{\dot{\phi}}{\phi} - \frac{\omega}{6}\frac{\dot{\phi}^2}{\phi^2} = \frac{\rho}{3\phi}, \quad (7)$$

$$(2+x)(\dot{H} + H^2) + (x^2+x+1)H^2 + \frac{\omega}{2}\frac{\dot{\phi}^2}{\phi^2} + (2+x)H\frac{\dot{\phi}}{\phi} + \frac{\ddot{\phi}}{\phi} = -\frac{(\gamma-1)\rho}{\phi}, \quad (8)$$

$$\ddot{\phi} + (3+x)H\dot{\phi} = \frac{(4-3\gamma)\rho}{4+3\omega}. \quad (9)$$

We will show that one interesting class of solutions is obtained for $x = -1$.

3 COSMOLOGICAL SOLUTIONS

For this particular value, Equation (7) gives straightforwardly $\rho = -\omega\dot{\phi}^2\big/2\phi$. After substituting into Equation (8), we find

$$\dot{H} + 2H^2 + \frac{2-\gamma}{2}\phi^{-2}\dot{\phi}^2 + H\frac{\dot{\phi}}{\phi} + \frac{\ddot{\phi}}{\phi} = 0. \quad (10)$$

To derive the solutions of these differential equations, we assume the time-dependence of the scalar field is in the form $\phi = t^p$ where p is a real parameter. For consistency, Equation (10) gives

$$ps + p - 1 = 2ps + p = p - 2, \tag{11}$$

and

$$(2\varepsilon - 1)p + 2\varepsilon^2 + \frac{2-\gamma}{2}p^2 = 0. \tag{12}$$

Equation (11) gives $ps = -1$ whereas Equation (9) gives

$$p = \frac{(1-2\varepsilon)(4+3\omega)}{4+7\omega-3\gamma\omega}. \tag{13}$$

The continuity equation gives in this case $p = 2 - 3\varepsilon\gamma$. The Hubble parameter varies as $H = \varepsilon t^{-1}$ and then the scale factor varies as $a(t) = t^{\varepsilon}$. Hence, one naturally expects that $\varepsilon > 0$ and moreover it is required to have $\varepsilon > 1$ in order to have an accelerated expansion. Accordingly, the energy density varies as $\rho = -(\omega/2)t^{-3\gamma\varepsilon}$. From Equation (12), we find then

$$p = \frac{-(2\varepsilon-1) \pm \sqrt{(2\varepsilon-1)^2 - 4(2-\gamma)}}{(2-\gamma)}, \tag{14}$$

and then from $p = 2 - 3\varepsilon\gamma$, we obtain

$$\varepsilon = \frac{-(6\gamma^2 - 9\gamma + 4) \pm \sqrt{36\gamma^3 - 63\gamma^2 + 24\gamma + 16}}{3\gamma(-3\gamma^2 + 6\gamma - 4)}. \tag{15}$$

Equation (15) shows that for $\varepsilon > 1$, we need $\gamma > 0$. These two conditions fulfill a decaying energy density with cosmic time. There is an easy way to check whether the positive sign in Equation (15) will lead to unrealistic values (negative or complex) for the parameter ε when $\gamma < 0$. We may address the following illustrative table.

Table 1 Values of the Parameters for Different Values of γ

γ	ε	p	ω	s	$a(t)$	$\rho(t)$	H	$w = \gamma - 1$
1	1.53	–2.59	–0.5	0.38	$t^{1.53}$	$0.25t^{-4.59}$	$1.53\phi^{0.38}$	0
4/3	1.36	–3.44	–1.33	0.29	$t^{1.36}$	$0.66t^{-5.44}$	$1.36\phi^{0.29}$	1/3
1/2	1.94	–0.91	≈ -2	1.2	$t^{1.94}$	$1.08t^{-2.91}$	$1.94\phi^{1.2}$	–1/2
1/4	3.2	–0.4	–1.45	2.5	$t^{3.2}$	$0.725t^{-2.4}$	$3.2\phi^{2.5}$	–3/4

It is notable from Table 1 that we have transitions from inflation to deceleration to accelerated epochs. However, the BD parameter is different from the one obtained in the low-energy limit of the bosonic string theory which is $\omega = -1$ (Callan et al. 1985). In our framework, $\omega < 0$ turns out to be negative and this result properly agrees with the conclusions of some recent works that the Brans-Dicke parameter needs to be negative for a successful explanation of the accelerated expansion of the universe (Bertolami & Martins 2000; Banerjee & Pavón 2001; Sen & Seshadri 2003). Though the universe in our framework is described by five-dimensional spacetime, the fifth dimension decays as $b(t) \approx a^{-1}(t)$ and hence at the end of time, $5D \to 4D$. Although the gravitational coupling constant is almost constant in four-dimensions or varies slowly (Turyshev et al. 2004), $G^{(5)} \propto \phi^{-1}$ is not a constant since it evolves with time. We find that the model is in best agreement with the supernovae data when the 5-dimensional Brans-Dicke coupling constant $-2 < \omega < -1.45$ which also happens to be the value required to satisfy the solar system experiments such as the baryon acoustic oscillation and is in agreement with recent studies (El-Nabulsi 2007, 2010). It is notable that in the standard framework, the BD coupling parameter range $-2 \leqslant \omega \leqslant -1.5$ violates the energy condition in the scalar field.

Another interesting parameter to discuss concerns the deceleration parameter $\bar{q}(t) \equiv -\ddot{a}a/\dot{a}^2$ which is directly related to the Hubble parameter by the relation $\bar{q} \equiv -\ddot{a}/H\dot{a} = -(q-1)/q$. The phenomenological two-parameter linear expansion $\bar{q}(z) = \bar{q}_0 + \bar{q}_1 z$ is useful; $\bar{q}_0$ and $\bar{q}_1$ are arbitrary constants to be compared with the values constrained by the Union supernovae dataset. However, recent astronomical observations (Riess et al. 1998; Cunha 2009; Perlmutter et al. 1999; Schmidt et al. 1998; Steinhardt et al. 1999; Persic et al. 1996; Riess et al. 2004; Alcaniz 2004) favor $\bar{q}_0 < 0$ for the late-time dynamics and $\bar{q}_1 > 0$ for the early-time dynamics or high energy limit with a high confidence level. In our approach, we have $\bar{q}_0 = -0.68$ for $\gamma = 1/4$ in accordance with the more recent results obtained by the Union SNe compilation as well as the recently extended dataset of distant supernovae observed with the Hubble Space Telescope, $\bar{q}_0 \leqslant -0.52$ with 68% confidence level. In our model and in particular for $\gamma = 1/4$, we find $\bar{q}_0 = -0.68$ which is very close to the value given by Wang et al. (2010) and Gong & Duan (2004). In terms of the redshift defined by $z = -1 + a_0/a$, the deceleration parameter $\bar{q}$ is determined easily from the evolution of the scale factor $H(t) = \varepsilon t^{ps}$. One easily obtains $\ln(1+z) = \varepsilon \int t^{ps} dt = \varepsilon \ln t$ for $ps = -1$ and hence $1+z = t^{\varepsilon} = \varepsilon^{\varepsilon} H^{-\varepsilon}$. Accordingly, the redshift is a function of the value of ε and this must be constrained carefully by observations making use of advanced computational techniques. However, we believe that for some special values of ε, e.g. $\varepsilon = 1.2$, we obtain $z \approx 0.8$ for $H_0 = 73.4^{+2.8}_{-3.8}$ km s^{-1} Mpc^{-1} ($h = 0.7$) (Spergel et al. 2007) which indicates that the accelerated expansion is a very recent phenomenon.

4 CONCLUSIONS AND PERSPECTIVES

In summary, in this work we have developed a procedure in which we regard our spacetime as a hypersurface embedded in a five-dimensional space, which is a solution of the Brans-Dicke field equations. We have conjectured that the Hubble parameter varies as $H = H(\phi) = \varepsilon \phi^s$ where ε is a positive parameter and s is some pending power index, and we explored the case where the extra-dimensions compactify as the visible dimensions expand as $b(t) \approx a^{-1}(t)$. These ansatzes lead to cosmological acceleration. We have found that the model exhibits a transition from decelerated power-law expansion and then enters a phase of power-law inflation in the radiation and pressureless epochs and finally undergoes a phase of accelerated expansion in the dark energy epoch with equation of state parameter $-1 < w = \gamma - 1 < 0$. For a very large time, the extra-dimensional scale factor decays in time and then we are left with an accelerated universe described by a 4D Friedman-Robertson-Walker spacetime. Further details and astrophysical implications are in progress.

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References

Alcaniz, J. S. 2004, Phys. Rev. D, 69, 083521
Arik, M., & Amon Susam, L. 2010, arXiv:1006.4252
Arik, M., Çalik, M., & Sheftel, M. B. 2008, International Journal of Modern Physics D, 17, 225
Armendariz-Picon, C., Mukhanov, V., & Steinhardt, P. J. 2001, Phys. Rev. D, 63, 103510
Bahrehbakhsh, A. F., Farhoudi, M., & Shojaie, H. 2010, General Relativity and Gravitation, 198
Banerjee, N., & Pavón, D. 2001, Phys. Rev. D, 63, 043504
Barrow, J. D. 1993, Phys. Rev. D, 47, 5329
Bento, M. C., Bertolami, O., & Sen, A. A. 2002, Phys. Rev. D, 66, 043507

Bergmann, P. G. 1968, International Journal of Theoretical Physics, 1, 25
Bertolami, O., & Martins, P. J. 2000, Phys. Rev. D, 61, 064007
Bhowmik, B. B., & Rajput, A. 2003, Indian J. pure appi. Math, 34, 1189
Bilić, N., Tupper, G. B., & Viollier, R. D. 2002, Phys. Lett. B, 535, 17
Brans, C., & Dicke, R. H. 1961, Physical Review, 124, 925
Brookfield, A. W., van de Bruck, C., Mota, D. F., & Tocchini-Valentini, D. 2006, Phys. Rev. D, 73, 083515
Callan, C. G., Friedan, D., Martinec, E. J., & Perry, M. J. 1985, Nuclear Physics B, 262, 593
Chen, S., Yang, S., Hao, X., & Liu, X. 2008, Chin. Phys. Lett., 25, 3162
Cunha, J. V. 2009, Phys. Rev. D, 79, 047301
Damour, T., & Nordtvedt, K. 1993, Phys. Rev. Lett., 70, 2217
El-Nabulsi, A. R. 2010, Ap&SS, 327, 111
El-Nabulsi, A. R. 2007, Fizika B, 16, 197
El-Nabulsi, A. R. 2009a, Brazilian Journal of Physics, 39, 107
El-Nabulsi, A. R. 2009b, Chin. Phys. Lett., 26, 090401
Fabris, J. C., Gonçalves, S. V. B., & de Souza, P. E. 2002, General Relativity and Gravitation, 34, 2111
Fabris, J. C., Gonçalves, S. V. B., & Ribeiro, R. D. S. 2006a, General Relativity and Gravitation, 38, 495
Fabris, J. C., Gonçalves, S. V. B., & Ribeiro, R. D. S. 2006b, Gravitation and Cosmology, 12, 49
Fardon, R., Nelson, A. E., & Weiner, N. 2004, J. Cosmol. Astropart. Phys., 10, 5
Gong, Y., & Duan, C. 2004, Classical and Quantum Gravity, 21, 3655
Guo, Z., Piao, Y., Zhang, X., & Zhang, Y. 2005, Phys. Lett. B, 608, 177
Hewett, J., & Spiropulu, M. 2002, Annual Review of Nuclear and Particle Science, 52, 397
Kalyana Rama, S. 1996, Physics Letters B, 373, 282
Kalyana Rama, S., & Ghosh, S. 1996, Phys. Lett. B, 383, 31
Kamenshchik, A., Moschella, U., & Pasquier, V. 2001, Phys. Lett. B, 511, 265
La, D., & Steinhardt, P. J. 1989, Phys. Rev. Lett., 62, 376
La, D., Steinhardt, P. J., & Bertschinger, E. W. 1989, Phys. Lett. B, 231, 231
Mathiazhagan, C., & Johri, V. B. 1984, Classical and Quantum Gravity, 1, L29
Nordtvedt, K., Jr. 1970, ApJ, 161, 1059
Ostriker, J. P., & Steinhardt, P. J. 1995, Nature, 377, 600
Peebles, P. J., & Ratra, B. 2003, Reviews of Modern Physics, 75, 559
Perlmutter, S., Aldering, G., Goldhaber, G., et al. 1999, ApJ, 517, 565
Persic, M., Salucci, P., & Stel, F. 1996, MNRAS, 281, 27
Randall, L., & Sundrum, R. 1999, Phys. Rev. Lett., 83, 3370
Reasenberg, R. D., Shapiro, I. I., MacNeil, P. E., et al. 1979, ApJ, 234, L219
Riess, A. G., Filippenko, A. V., Challis, P., et al. 1998, AJ, 116, 1009
Riess, A. G., Strolger, L., Tonry, J., et al. 2004, ApJ, 607, 665
Rubakov, V. A. 2001, Physics Uspekhi, 44, 871
Sadeghi, J., Setare, M. R., Banijamali, A., & Milani, F. 2008, Physics Letters B, 662, 92
Sahoo, B. K., & Singh, L. P. 2002, Modern Physics Letters A, 17, 2409
Schmidt, B. P., Suntzeff, N. B., Phillips, M. M., et al. 1998, ApJ, 507, 46
Sen, S., & Seshadri, T. R. 2003, International Journal of Modern Physics D, 12, 445
Serna, A., & Alimi, J. M. 1996, Phys. Rev. D, 53, 3074
Setare, M. R., & Saridakis, E. N. 2008a, Phys. Lett. B, 668, 177
Setare, M. R., & Saridakis, E. N. 2008b, J. Cosmol. Astropart. Phys., 9, 26
Spergel, D. N., Bean, R., & Doré, O., et al. 2007, ApJS, 170, 377
Steinhardt, P. J., Wang, L., & Zlatev, I. 1999, Phys. Rev. D, 59, 123504
Turyshev, S. G., Williams, J. G., Nordtvedt, K. Jr., et al. 2004, in Astrophysics, Clocks and Fundamental Constants (Lecture Notes in Physics, Berlin Springer Verlag), Vol. 648, eds. S. G. Karshenboim & E. Peik,

(Berlin: Springer Verlag), 311
Veneziano, G. 1996, in 3rd Paris Cosmology Colloquium, ed. M. Rowan-Robinson, 234–252
Wagoner, R. V. 1970, Phys. Rev. D, 1, 3209
Wang, W., & Yang, S. 2005, Chin. Phys. Lett., 22, 1296
Wang, W. F., Shui, Z., & Tang, B. 2010, Chin. Phys. B, 19, 119801
Weinberg, E. J. 1989, Phys. Rev. D, 40, 3950
Xia, J., Feng, B., & Zhang, X. 2005, Modern Phys. Lett. A, 20, 2409
Zhao, G., Xia, J., Zhang, X., & Feng, B. 2007, International Journal of Modern Physics D, 16, 1229