RAA 2015 Vol. **15** No. **2**, 191–198 doi: 10.1088/1674–4527/15/2/003
http://www.raa-journal.org *http://www.iop.org/journals/raa*

***R**esearch in*
***A**stronomy and*
***A**strophysics*

Searching for α variation and cosmic acceleration in the generalized BSBM theory with tachyonic potential

Hossein Farajollahi[1,2] and Fatemeh Tayebi[1]

[1] Department of Physics, University of Guilan, Namjou BLV, Rasht, Iran; *hosseinf@guilan.ac.ir*
[2] School of Physics, University of New South Wales, Sydney, NSW, 2052, Australia

Received 2013 December 2; accepted 2014 May 13

Abstract We consider the BSBM (Bekenstein, Sandvik, Barrow and Magueijo) cosmological model in the presence of tachyon potential with the aim of studying the stability of the model and test it against observations. The phase space analysis shows that from fourteen critical points that represent the state of the universe, only one is stable. With a small perturbation, the universe transits from a state of unstable deceleration to stable acceleration. The stability analysis combined with the best fitting process imposes constraints on the cosmological parameters that are in agreement with observation. In the BSBM theory, the variation of fundamental constants is driven from variation of a scalar field. The tachyonic scalar field, responsible for both variation of fundamental constants and universal acceleration, is reconstructed.

Key words: cosmology: theory — cosmology: observations— cosmological parameters

1 INTRODUCTION

The assumption of the constancy of fundamental constants is crucial in cosmology where the redshift measures the expansion of the universe. The possibility of varying constants dramatically changes our understanding of the universe and appropriate modifications should be made to the cosmologic models to address this issue. The assumption of varying fundamental constants was pioneered by the work of Dirac (1937). Intense investigation in this field suggests a new connection between astrophysics, cosmology and high-energy physics that is complementary to cosmology of the early universe. In particular, the observation of the variability of fundamental constants constitutes one of the few ways to examine higher dimensional theories.

From all fundamental constants of nature, the fine structure constant, α, dubbed the "coupling constant" of electromagnetic interactions, can be derived from other constants as (Hagiwara et al. 2002)

$$\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c}\,, \tag{1}$$

where c is the speed of light in a vacuum, $\hbar \equiv h/2\pi$ is the reduced Planck constant, e is the electron charge magnitude and ϵ_0 is the permittivity of free space. The current value of α on Earth is $\alpha_0 \approx 1/137.035$ (Hagiwara et al. 2002).

Many authors have studied the theoretical possibilities of time and spatial variations of the fine structure constant during the history of the universe (Ichikawa & Kawasaki 2004; Das & Kunstatter 2003; Webb et al. 2003; Murphy et al. 2003a, 2008; Barrow & Shaw 2008; Parkinson et al. 2004). In this paper, we focus on time variations of α which can be measured by using the "time shift density parameter" as

$$\frac{\Delta\alpha}{\alpha} \equiv \frac{\alpha(z)-\alpha_0}{\alpha_0}\,, \tag{2}$$

where $\alpha(z)$ is the value of the fine structure constant at redshift z.

The observational evidence from quasar absorption spectra indicates that the fine structure constant might change with cosmological time; smaller than its present value by $\frac{\Delta\alpha}{\alpha} \sim 10^{-5}$ at redshifts in the range $z \sim 1-3$ (Webb et al. 1999, 2001; Murphy et al. 2001, 2003b). From e.g. Granda & Oliveros (2009), variation of the fine structure constant may be due to variation in the speed of light, c, (Moffat 1993; Albrecht & Magueijo 1999; Barrow 1999) or electric charge, e, (Bekenstein 1982). While in the first case the Lorentz invariance is violated, in the second one local gauge and Lorentz invariance are both preserved and the theory is generally covariant. Bekenstein's original theory regards c and $\hbar$ as constants and attributes variations in α to changes in e, or the permittivity of free space. He makes a set of assumptions to obtain a reasonable modification of Maxwell's equations to take into account the effect of the variation of the elementary charge, e (Bekenstein 1982). This is done by letting e assume the value of a real scalar field which varies in space and time such that $e_0 \to e = e_0\epsilon(x^\mu)$, where ϵ is a dimensionless dynamic scalar field and e_0 is a constant denoting the present value of e. Since e is the electromagnetic coupling, the ϵ field couples to the gauge field as ϵA_μ in the Lagrangian. The unique gauge-invariant and shift symmetric Lagrangian for the modified electromagnetic field can be written as $\mathcal{L}_{\rm em} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$, so that $F_{\mu\nu} = \epsilon^{-1}[\partial_\mu(\epsilon A_\nu) - \partial_\nu(\epsilon A_\mu)]$ is the generalized electromagnetic tensor (Maity & Chen 2011a,b). Bekenstein did not take into account the effect of the field ϵ in the Einstein equations and only studied the time variation of ϵ in a matter dominated universe.

Sandvik, Barrow and Magueijo have generalized the scalar theory by Bekenstein in order to include gravitational effects of the field, ϵ, responsible for variations of α. They replaced the dilaton with a cosmological scalar field (Sandvik et al. 2002). To simplify calculations, they invoked a transformation by defining an auxiliary gauge potential $a_\mu = \epsilon A_\mu$ and field tensor $f_{\mu\nu} = \epsilon F_{\mu\nu} = \epsilon^{-1}(\partial_\mu(a_\nu) - \partial_\nu(a_\mu))$, and to simplify further: $\epsilon \to \phi \equiv \ln\epsilon$. The total action describing the dynamics of the universe with a varying-α becomes (Sandvik et al. 2002; Maity & Chen 2011a,b)

$$S = \int {\rm d}x^4\sqrt{-g}\Big[\mathcal{L}_{\rm grav} + \mathcal{L}_\phi + \mathcal{L}_{\rm em}e^{-2\phi} + \mathcal{L}_{\rm m}\Big]\,, \tag{3}$$

where $\mathcal{L}_\phi = -\frac{\omega}{2}\partial_\mu\phi\partial^\mu\phi$ and $\mathcal{L}_{\rm em} = -\frac{1}{4}f_{\mu\nu}f^{\mu\nu}$. The gravitational Lagrangian is the usual $\mathcal{L}_{\rm grav} = \frac{1}{16\pi G}\mathcal{R}$, with $\mathcal{R}$ the curvature scalar and G the Newtonian constant gravity. The matter Lagrangian is denoted by $\mathcal{L}_{\rm m}$. Since the scalar field is generally coupled to gauge fields, its cosmological evolution naturally leads to a change in the effective fine structure constant. This can provide an interesting possibility to explain the observational data on the variation of α (Sandvik et al. 2002; Maity & Chen 2011a,b; Garousi et al. 2005).

The variation in fine structure constant α can be studied in different types of dark energy (DE) models; driven from a scalar field coupled to the electromagnetic field (Barrow & Li 2008), or from a Dirac-Born-Infeld scalar field (Garousi et al. 2005; Wei 2009; Wei & Cai 2005). Independently, in scalar-tensor gravity (Mainini et al. 2005; Li et al. 2005, 2007; Granda & Oliveros 2009), a scalar field coupled to the curvature (Arias et al. 2003; Kim 2005; Setare & Jamil 2010) or matter field (Brax et al. 2004; Steffen 2010) represents DE and thus accounts for universal acceleration. Integration of the two above couplings encourages us to consider a model in which such a cosmological scalar field drives both the variation of cosmological constants (such as α) and universal acceleration. Farajollahi & Salehi (2012a,b) have already studied such a cosmological model by considering the Bekenstein, Sandvik, Barrow and Magueijo (BSBM) theory and assume the scalar field in the model is responsible for varying α and cosmic acceleration. So far, the varying α models driven by either a quintessence scalar field (Avelino 2008; Olive & Pospelov 2002) or a phantom field with negative model parameter ω (Farajollahi et al. 2012) in the BSBM model (Mota & Barrow 2004a,b; Barrow et al. 2004) have been extensively investigated in the literature. Independently, Bisabr assumes that if there exists a matter system in a Jordan frame, then it interacts with the scalar field in an Einstein frame due to the conformal transformations which may lead to changes in fundamental constants (Wei et al. 2011). As an example, he investigates the scenario of variation of the fine structure constant in a general $f(R)$ theory. In an extension of BSBM, the coupling between the scalar field and the electromagnetic field could also be generalized in the form of a general function $B_{\rm F}(\phi)$ and used to investigate α variation (Farajollahi & Salehi 2012a; Marra & Rosati 2005).

According to observations, all cosmological models must be constrained by observational data of Type Ia Supernovae (SNe Ia) if they are used to explain current universal acceleration. Independently, for a cosmological model to interpret α variation, it has to also be constrained by the relevant observational data. In the work of Farajollahi & Salehi (2012a), the BSBM model is constrained with observational data about distance modulus and tested against quasar absorption spectra.

From string theory, the spectrum of strings does contain a tachyon field (a negative mass squared vibration $m^2 < 0$) which guarantees faster-than-light speed (Escamilla et al. 2013). Naively, the mass of a scalar field is given by the second derivative of the potential $V(\varphi)$ with respect to the field, e.g. $m^2 = {\rm d}V^2/{\rm d}\varphi^2$ (de la Macorra et al. 2006). Although in field theory the scalar field is responsible for instabilities (Frolov et al. 2002; Sen 1998, 2006; Farajollahi et al. 2011a), in cosmology it is considered to be a candidate for DE (Copeland et al. 2005; Debnath 2008; Avelino et al. (2011)). In this work, we will see if the tachyon field is also responsible for α variation, so we assume a BSBM theory while the potential is a tachyonic potential.

We organize this paper as follows: in Section 2 we solve the field equations by best fitting the model parameters with the quasar absorption spectra using the chi-squared method. A phase space analysis is given in Section 3. With stability analysis, we obtain attractor solutions of the dynamical system asymptotically. As a result, we avoid fine tuning problems since the trajectories in the phase space lie along a common track despite beginning from different initial conditions (Farajollahi & Salehi 2012a,b). In Section 4, the model is tested with observational data about the Hubble parameter and also observational data of SNe Ia used to compute the distance modulus. We also calculate the reconstructed deceleration and jerk parameters to verify cosmic acceleration occurs. A reconstructed scalar field variation responsible for α variation with the best fitted model parameters is also given. Conclusions are provided in Section 5.

2 GENERAL SET UP

The scalar field Lagrangian with a tachyon potential is $\mathcal{L}_\phi = -V(\phi)\sqrt{1-\partial_\mu\phi\partial^\mu\phi}$ (Farajollahi et al. 2011b; Farajollahi & Salehi 2011). By substituting the above into the action (3) we have (Barrow & Lip 2012; Farajollahi & Salehi 2012a,b)

$$S = \int {\rm d}x^4\sqrt{-g}\left[\frac{\mathcal{R}}{16\pi G} - V(\phi)\sqrt{1-\partial_\mu\phi\partial^\mu\phi} - \frac{1}{4}{\rm e}^{-2\phi}f_{\mu\nu}f^{\mu\nu} + \mathcal{L}_{\rm m}\right]. \tag{4}$$

To obtain the cosmological equations, we vary the action (4) with respect to the metric to give the generalized Einstein equation

$$G_{\mu\nu} = 8\pi G\Big(T_{\mu\nu}{\rm m} + T^{\phi}_{\mu\nu} + T^{\rm em}_{\mu\nu}\Big). \tag{5}$$

From the 00-component and ii-component of the field Equation (5) in Friedmann-Robertson-Walker cosmology, we can obtain the Friedmann equations as

$$H^2 = \frac{8\pi G}{3}\left[\rho_{\rm m}\,(1+|\zeta|{\rm e}^{-2\phi})+\rho_{\rm r}\,{\rm e}^{-2\phi}+\frac{V(\phi)}{\sqrt{1-\dot{\phi}^2}}\right], \quad (6)$$

$$\dot{H} = -\frac{8\pi G}{2}\left[\rho_{\rm m}\,(1+|\zeta|{\rm e}^{-2\phi})+\frac{4}{3}\rho_{\rm r}\,{\rm e}^{-2\phi}+\frac{V(\phi)\dot{\phi}}{\sqrt{1-\dot{\phi}^2}}\right], \quad (7)$$

where $|\zeta| \equiv \frac{\mathcal{L}_{\rm em}}{\rho_{\rm m}}$. We assume the matter field filling the universe is dark matter, then the conservation equation for the matter density is

$$\dot{\rho_{\rm m}} + 3H\rho_{\rm m} = 0\,. \quad (8)$$

The equation of motion for ϕ that carries the α variations comes from variation of the action (4) with respect to the scalar field ϕ

$$\ddot{\phi} + (1-\dot{\phi}^2)\Big(3H\dot{\phi}+\frac{V'}{V}\Big) = 2|\zeta|{\rm e}^{-2\phi}\rho_{\rm m}\,, \quad (9)$$

where prime means derivative with respect to the scalar field. The right-hand side of Equation (9) shows a source term for ϕ and includes all the matter fields, including relativistic and non-relativistic matter, that interact electromagnetically. Obviously, $\mathcal{L}_{\rm em}$ vanishes due to a sea of pure radiation since $\mathcal{L}_{\rm em} = (E^2 - B^2)/2 = 0$. Therefore, a nearly pure electrostatic or magnetostatic energy associated with non-relativistic particles causes a dynamical ϕ (Sandvik et al. 2002).

For stability analysis, we reduce the second order coupled nonlinear differential equations into compact and neat first order ones by introducing new variables as (Farajollahi et al. 2011b; Farajollahi & Salehi 2011),

$$x = \frac{\rho_{\rm m}}{3H^2}, \quad y = \dot{\phi}, \quad z = \frac{V}{3H^2}, \quad \tilde{\alpha} = {\rm e}^{2\phi}, \quad u = \frac{1}{H}\,, \quad (10)$$

where $\tilde{\alpha} = \tilde{\alpha}_0\,\frac{\alpha}{\alpha_0}$. Using Equations (7)–(9), the evolution equations of these variables become

$$x' = 3x\Big[-1+x+\frac{x}{\tilde{\alpha}}|\zeta|+\frac{zy}{\sqrt{1-y^2}}\Big], \quad (11)$$

$$\tilde{\alpha}' = 2\tilde{\alpha}yu\,, \quad (12)$$

$$z' = z\Big[\beta+3x+3\frac{x}{\tilde{\alpha}}|\zeta|+\frac{3zy}{\sqrt{1-y^2}}\Big], \quad (13)$$

$$y' = -y\Big[(1-y^2)\Big(3+\frac{\beta}{y^2}\Big)-\frac{6|\zeta|x}{uy\tilde{\alpha}}\Big], \quad (14)$$

$$u' = \frac{3}{2}u\Big[x+\frac{x}{\tilde{\alpha}}|\zeta|+\frac{zy}{\sqrt{1-y^2}}\Big], \quad (15)$$

where an exponential behavior for the potential function is assumed, $\beta = \frac{V'}{V}$. Also, the Friedmann constraint (6) in terms of the new dynamical variables becomes

$$1 = x + |\zeta|\frac{x}{\tilde{\alpha}} + \frac{z}{\sqrt{1-y^2}}\,. \quad (16)$$

We solve the above equations by best fitting the model parameters and initial conditions with the observational data of the quasar absorption spectra for $\Delta\alpha/\alpha$ using the χ^2 function

$$\chi^2(\beta; x_0, \tilde{\alpha}_0, y_0, u_0) = \sum_{i=1}^{49} \frac{[\Delta\alpha/\alpha|_i^{\rm the}\,(z_i|\beta; x_0, \tilde{\alpha}_0, y_0, u_0) - \Delta\alpha/\alpha|_i^{\rm obs}]^2}{\sigma_i^2}\,. \tag{17}$$

From numerical computation, Table 1 shows the best-fitted model parameters with $\zeta = 1 \times 10^{-4}$. The stability of the solutions will be discussed in the next section.

Table 1 Best-Fitted Model Parameters and Initial Conditions

Parameter	β	x_0	$\tilde{\alpha}_0$	y_0	H_0	$\chi^2_{\rm min}/{\rm dof}$
	0.05	0.29	0.0002	1×10^{-5}	71.9	0.7308329

3 PHASE SPACE ANALYSIS

A linear perturbation of the system exhibits fourteen critical points, all of which are unstable except for one. Table 2 shows the coordinates of the points and their stability status. It is important to note that an analysis of the stability is performed after we constrain the model parameters with observational data.

Table 2 Best Fitted Critical Points

Point	${\rm cp}_1$	${\rm cp}_2$	${\rm cp}_3$	${\rm cp}_4$	${\rm cp}_5$	${\rm cp}_6$	${\rm cp}_7$
(x, y, z, u)	(0,0,1.016,0)	$(x, 1, 0, u)$	$(x, -1, 0, u)$	$(x, 1, 0, 0)$	$(x, -1, 0, 0)$	(1, 1, 0, 0)	$(1, -1, 0, 0)$
Stability	stable	unstable	unstable	unstable	unstable	unstable	unstable
Point	${\rm cp}_8$	${\rm cp}_9$	${\rm cp}_{10}$	${\rm cp}_{11}$	${\rm cp}_{12}$	${\rm cp}_{13}$	${\rm cp}_{14}$
(x, y, z, u)	$(1, 1, 0, u)$	$(1, -1, 0, u)$	$(0, -1, 0, 0)$	(0, 1, 0, 0)	$(0, -0.016, 0.99, 0)$	$(0, -1, 0, u)$	$(0, 1, 0, u)$
Stability	unstable	unstable	unstable	unstable	unstable	unstable	unstable

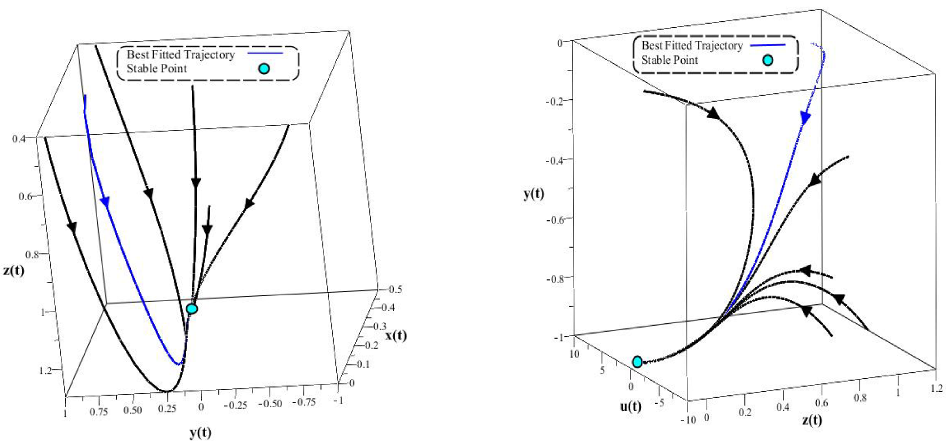

Fig. 1 The attractor property of the dynamical system in the three dimensional phase plane.

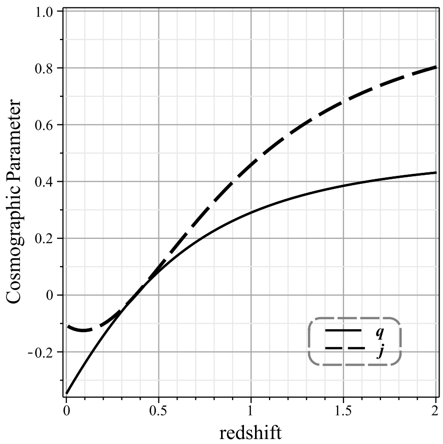

Fig. 2 The best-fitted deceleration and jerk parameters as a function of redshift.

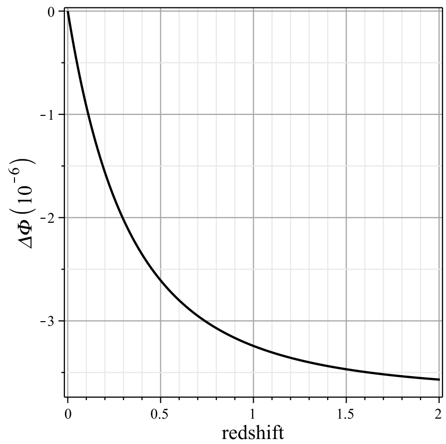

Fig. 3 The reconstructed scalar field ϕ as a function of redshift.

A three dimensional phase space of the solution is illustrated in Figure 1. The left panel in Figure 1 shows that the trajectories leaving the unstable critical points in the past and moving towards the stable critical point cp_1 in the future. The best-fitted model parameter trajectory is also shown by a blue dashed line. Similarly, the projection into three dimensional space $(u(t), y(t), z(t))$ is shown in Figure 1 (right panel).

To test the model against observations and confirm the best-fitted model parameters, in the next section we perform cosmological tests.

4 COSMOLOGICAL TEST

One of the most popular tests is to monitor the dynamics of the reconstructed deceleration and jerk parameters. These parameters, in terms of stability variables, are given by

$$q = 3x/2 + \frac{3x}{2\tilde{\alpha}}|\zeta| + \frac{3zy}{2\sqrt{1-y^2}} - 1, \tag{18}$$

$$j = q + 2q^2 - \frac{\dot{q}}{H}. \tag{19}$$

Figure 2 shows these two kinematical parameters for the best-fitted model parameters and stable trajectories. The current values of the deceleration and jerk parameters are $q = -0.34$ and $j = -0.11$, which are within the range of observationally based estimates, $q_0 \in (-1.3, -0.2)$ and $j_0 \in (-0.3, +5.9)$ (Visser & Wiltshire 2004).

The scalar field responsible for both α variation and universal acceleration using the best-fitted model parameters is also reconstructed. From the above equations and for tachyon fields with faster-than-light speed, we expect $\Delta\phi = \phi - \phi_0$. Figure 3 shows the scalar field variation which is in agreement with the theory.

5 CONCLUSIONS

In this paper, we study the BSBM theory in the presence of a tachyon potential. The mathematical stability of the model is analyzed and the parameters in the model are constrained with observational data. The combination of stability analysis and the best fitting procedure guarantees the validity of the model. We find that among fourteen critical points that represent the state of the universe, only one critical point is stable and all others represent an unstable universe, which are not acceptable. With a small perturbation, the universe moves from an unstable decelerating state in the past towards a stable accelerating state.

Our motivation to study the stability of the BSBM model with tachyon potential is twofold. First, we show that the field in the model that acts as a candidate for DE can explain the current universal acceleration. We examine the performance of the model by numerically computing the cosmological parameters such as deceleration and jerk parameters. We find that the current values of both of these parameters are within the observational range. Second, we reconstruct the scalar field in BSBM theory that is responsible for fine structure constant variation.

Acknowledgements One of the authors, Hossein Farajollahi, is thankful to the University of New South Wales for the hospitality of the Physics Department and for the Gordon Godfrey Award.

References

Albrecht, A., & Magueijo, J. 1999, Phys. Rev. D, 59, 043516

Arias, O., Gonzalez, T., Leyva, Y., & Quiros, I. 2003, Classical and Quantum Gravity, 20, 2563

Avelino, P. P. 2008, Phys. Rev. D, 78, 043516

Avelino, P. P., Losano, L., & Rodrigues, J. J. 2011, Physics Letters B, 699, 10

Barrow, J. D. 1999, Phys. Rev. D, 59, 043515

Barrow, J. D., Kimberly, D., & Magueijo, J. 2004, Classical and Quantum Gravity, 21, 4289

Barrow, J. D., & Li, B. 2008, Phys. Rev. D, 78, 083536

Barrow, J. D., & Shaw, D. J. 2008, Phys. Rev. D, 78, 067304

Barrow, J. D., & Lip, S. Z. W. 2012, Phys. Rev. D, 85, 023514

Bekenstein, J. D. 1982, Phys. Rev. D, 25, 1527

Brax, P., van de Bruck, C., Davis, A.-C., Khoury, J., & Weltman, A. 2004, Phys. Rev. D, 70, 123518

Copeland, E. J., Garousi, M. R., Sami, M., & Tsujikawa, S. 2005, Phys. Rev. D, 71, 043003

Das, S., & Kunstatter, G. 2003, Classical and Quantum Gravity, 20, 2015

de la Macorra, A., Filobello, U., & Germán, G. 2006, Physics Letters B, 635, 355

Debnath, U. 2008, Classical and Quantum Gravity, 25, 205019

Dirac, P. A. M. 1937, Nature, 139, 323

Escamilla-Rivera, C., García-Jiménez, G., Loaiza-Brito, O., & Obregón, O. 2013, Classical and Quantum Gravity, 30, 035005

Farajollahi, H., & Salehi, A. 2011, Phys. Rev. D, 83, 124042

Farajollahi, H., Salehi, A., & Shahabi, A. 2011a, J. Cosmol. Astropart. Phys., 10, 014

Farajollahi, H., Salehi, A., Tayebi, F., & Ravanpak, A. 2011b, J. Cosmol. Astropart. Phys., 5, 017

Farajollahi, H., & Salehi, A. 2012a, J. Cosmol. Astropart. Phys., 2, 041

Farajollahi, H., & Salehi, A. 2012b, J. Cosmol. Astropart. Phys., 11, 002

Farajollahi, H., Tayebi, F., Milani, F., & Enayati, M. 2012, Ap&SS, 337, 773

Frolov, A., Kofman, L., & Starobinsky, A. 2002, Physics Letters B, 545, 8

Garousi, M. R., Sami, M., & Tsujikawa, S. 2005, Phys. Rev. D, 71, 083005

Granda, L. N., & Oliveros, A. 2009, Physics Letters B, 671, 199

Hagiwara, K., Hikasa, K., Nakamura, K., et al. 2002, Phys. Rev. D, 66, 010001

Ichikawa, K., & Kawasaki, M. 2004, Phys. Rev. D, 69, 123506

Kim, H. 2005, MNRAS, 364, 813

Li, C., Holz, D. E., & Cooray, A. 2007, Phys. Rev. D, 75, 103503

Li, M., Feng, B., & Zhang, X. 2005, J. Cosmol. Astropart. Phys., 12, 002

Mainini, R., Colombo, L. P. L., & Bonometto, S. A. 2005, ApJ, 632, 691

Maity, D., & Chen, P. 2011a, Phys. Rev. D, 83, 083516
Maity, D., & Chen, P. 2011b, Phys. Rev. D, 84, 026008
Marra, V., & Rosati, F. 2005, J. Cosmol. Astropart. Phys., 5, 011
Moffat, J. W. 1993, International Journal of Modern Physics D, 2, 351
Mota, D. F., & Barrow, J. D. 2004a, MNRAS, 349, 291
Mota, D. F., & Barrow, J. D. 2004b, Physics Letters B, 581, 141
Murphy, M. T., Webb, J. K., Flambaum, V. V., et al. 2001, MNRAS, 327, 1208
Murphy, M. T., Webb, J. K., Flambaum, V. V., et al. 2001b, MNRAS, 327, 1208
Murphy, M. T., Webb, J. K., Flambaum, V. V., & Curran, S. J. 2003a, Ap&SS, 283, 577
Murphy, M. T., Webb, J. K., & Flambaum, V. V. 2003b, MNRAS, 345, 609
Murphy, M. T., Webb, J. K., & Flambaum, V. V. 2008, MNRAS, 384, 1053
Olive, K. A., & Pospelov, M. 2002, Phys. Rev. D, 65, 085044
Parkinson, D., Bassett, B. A., & Barrow, J. D. 2004, Physics Letters B, 578, 235
Sandvik, H. B., Barrow, J. D., & Magueijo, J. 2002, Physical Review Letters, 88, 031302
Sen, A. 1998, Journal of High Energy Physics, 8, 012
Sen, A. A. 2006, Phys. Rev. D, 74, 043501
Setare, M. R., & Jamil, M. 2010, Physics Letters B, 690, 1
Steffen, J. H. 2010, in Proceedings of the 35th International Conference of High Energy Physics (ICHEP 2010)
Visser, M., & Wiltshire, D. L. 2004, Classical and Quantum Gravity, 21, 1135
Webb, J. K., Flambaum, V. V., Churchill, C. W., Drinkwater, M. J., & Barrow, J. D. 1999, Physical Review Letters, 82, 884
Webb, J. K., Murphy, M. T., Flambaum, V. V., et al. 2001, Physical Review Letters, 87, 091301
Webb, J. K., Murphy, M. T., Flambaum, V. V., & Curran, S. J. 2003, Ap&SS, 283, 565
Wei, H. 2009, Physics Letters B, 682, 98
Wei, H., & Cai, R.-G. 2005, Phys. Rev. D, 71, 043504
Wei, H., Ma, X.-P., & Qi, H.-Y. 2011, Physics Letters B, 703, 74