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M. Vijaya Santhi, V. U. M. Rao, Y. Aditya

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Bianchi type-VI_0 modified holographic Ricci dark energy model in a scalar-tensor theory

M.Vijaya Santhi, V.U.M.Rao, Y.Aditya

Department of Applied Mathematics, Andhra University, Visakhapatnam-530003, India
gv.santhi@live.com

Abstract

In this paper, we consider Bianchi type-VI_0 space-time filled with anisotropic modified holographic Ricci dark energy (MHRDE) in a scalar tensor theory proposed by Brans-Dicke (Phys. Rev. **124**, 925, 1961). The field equations in this scalar-tensor theory, have been solved for the following physically relevant assumptions: (i) the scalar field (ϕ) is proportional to average scale factor ($a(t)$), (ii) Expansion scalar (θ) in the model is proportional to shear scalar (σ). It has been observed that the presented universe is in accelerating phase at present epoch, which is in good agreement with the recent astronomical observations. We have also discussed some other properties of the obtained model.

Key words: Bianchi type-VI_0 metric, Deceleration parameter, holographic dark energy, cosmology, Brans-Dicke theory.

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1 Introduction

The recent scenario of the accelerated expansion of the universe confirmed through different observational schemes by Riess et al. [1] and Perlmutter et al. [2]. Cosmological observations and cosmic microwave background data suggest [3, 4] that the universe is spatially flat and is dominated by an exotic component with large negative pressure dubbed as dark energy. It is also believed that dark energy occupies 73% of the energy of our universe, dark matter occupies 23% and the rest energy is baryonic matter [5,6]. In order to explain this late time acceleration, two main different approaches have been advocated: one is to construct different dark energy candidates and the other is the modification of Einsteins theory of gravitation. Among the several modifications Brans-Dicke [7] and Saez-Ballester [8] scalar-tensor theories are significant.

Brans and Dicke [7] introduced a scalar-tensor theory of gravitation involving a scalar function (ϕ) in addition to the familiar general relativistic metric tensor. In this theory the scalar field has the dimension of inverse of the gravitational constant and its role is confined to its effects on gravitational field equations. Reddy and Lakshmi [9] have studied Kaluza-Klein dark energy model in Brans-Dicke theory of gravitation. Rao et al. [10] have discussed FRW holographic dark energy cosmological model in Brans-Dicke theory of gravitation. Rao and Jayasudha [11] have discussed Bianchi type-V anisotropic dark energy models in Brans-Dicke theory of gravitation. Recently, Santhi et al. [12] have discussed holographic dark energy model with generalized Chaplygin gas in this theory of gravitation. Rao and Prasanthi [13] have studied Bianchi type VI_0 generalized ghost pilgrim dark energy model in Brans-Dicke theory of gravitation.

In recent years, holographic dark energy models based on holographic principle have received considerable attention. According to the holographic principle, the number of degrees of freedom in a bounded system should be finite and is related to the area of its boundary [14]. It is argued that this model may solve the cosmological constant problem and some other issues. Cohen et al. [15] and Hsu [16] are some of the authors who have investigated several aspects of holographic dark energy. Gao et al. [17] have proposed a holographic dark energy model, where the future event horizon is replaced by the inverse of the Ricci scalar curvature, and this model is named as *holographic Ricci dark energy model*, whose length scale is the inverse of the Ricci curvature scalar, i.e., $L \approx \mid R \mid^{\frac{-1}{2}}$. Granda and Oliveros [18] suggested a new holographic Ricci dark energy model with energy density

$$\rho_\Lambda = 3M_p^2(\beta_1 H^2 + \beta_2 \dot{H}), \tag{1}$$

Later, Chen and Jing [19] modified this model by assuming the density of dark energy contains the Hubble parameter H, the first order and the second order derivatives (i.e., $\dot{H}$ and $\ddot{H}$). The expression of the energy density of modified holographic Ricci dark energy (MHRDE) is given by

$$\rho_\Lambda = 3M_p^2(\beta_1 H^2 + \beta_2 \dot{H} + \beta_3 \ddot{H} H^{-1}) \tag{2}$$

where M_p^2 is the reduced Planck mass, β_1, β_2 and β_3 are three arbitrary dimensionless parameters.

Spatially homogeneous and anisotropic cosmological models play a significant role in the description of large scale behavior of universe and such models have been widely studied in the framework of general relativity in search of a realistic picture of the universe in its early stages. Though Bianchi type-I universe is the prime candidate for studying the possible effects of an anisotropy in the early universe on present-day observations, there are few other models like Bianchi type-II, III, V, VI_0, $VIII$ and IX which describe anisotropic space-times which generate particular interest among physicists. Recently, Kiran et al. [20], Santhi et al. [21] are some of the authors who have investigated some Bianchi dark energy cosmological models in Brans-Dicke scalar-tensor theory of gravitation. Very recently, Santhi et al. [22] have studied some Bianchi type dark energy models in general relativity, while Das and Sultana [23, 24] have studied Bianchi type-II and VI_0 anisotropic MHRDE cosmological models in general relativity. Santhi et al. [25] have investigated Bianchi type-VI_0 MHRDE model in Saez-Ballester theory of gravitation.

Motivated by the above discussion and investigations, we consider anisotropic Bianchi type-VI_0 metric filled with anisotropic modified holographic Ricci dark energy (MHRDE) in Brans and Dicke [7] scalar-tensor theory of gravitation.

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2 Metric and field equations

We consider spatially homogeneous Bianchi type-VI_0 metric as

$$ds^2 = dt^2 - A^2(t)dx^2 - B^2(t)e^{-2x}dy^2 - C^2(t)e^{2x}dz^2, \tag{3}$$

where A, B, C are functions of cosmic time t only.

Brans-Dicke [7] field equations for combined scalar and tensor fields are

$$R_{ij} - \frac{1}{2}Rg_{ij} = -8\pi\phi^{-1}(T_{ij} + \overline{T}_{ij}) - w\phi^{-2}\left(\phi_{,i}\phi_{,j} - \frac{1}{2}g_{ij}\phi_{,\mu}\phi^{,\mu}\right) - \phi^{-1}\left(\phi_{i;j} - g_{ij}\phi^{;\mu}_{;\mu}\right), \tag{4}$$

and

$$\phi^{;\mu}_{;\mu} = 8\pi T(3 + 2w)^{-1} \tag{5}$$

where $T_{ij}, \overline{T}_{ij}$ are stress energy tensors of matter and dark energy respectively, T is trace of energy momentum tensors, w is a dimensionless coupling constant, comma and semicolon denote partial and covariant differentiation respectively.
Also, we have energy conservation equation as

$$(\overline{T}^{ij} + T^{ij})_{;j} = 0, \tag{6}$$

which is a consequence of field equations (4) and (5). We are dealing with pressure less dark matter and an anisotropic dark energy whose energy-momentum tensors are in the following form:

$$T_i^j = diag[1, 0, 0, 0]\rho_m, \tag{7}$$
$$\overline{T}_i^j = diag[\rho_\Lambda, -p_x, -p_y, -p_z] \tag{8}$$

We parametrize equation (8) as follows:

$$\begin{aligned}\overline{T}_i^j &= diag[1, -\omega_x, -\omega_y, -\omega_z]\rho_\Lambda \\ &= diag[1, -\omega_\Lambda, -(\omega_\Lambda + \delta_y), -(\omega_\Lambda + \delta_z)]\rho_\Lambda\end{aligned} \tag{9}$$

where ρ_Λ is the energy density of the dark energy; p_x, p_y and p_z are the pressures and ω_x, ω_y and ω_z are the directional equation of parameter (EoS) parameters of the fluid. Now, parameterizing the deviation from isotropy by considering $\omega_x = \omega_\Lambda = \frac{p_\Lambda}{\rho_\Lambda}$ and then introducing deviations from EoS parameter (skewness parameters) δ_y and δ_z on the y and z axes respectively.

The Brans-Dicke theory field equations (4)-(5) for the metric (3) with the help of (7) and

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(9) can be written as

$$\frac{\ddot{B}}{B}+\frac{\ddot{C}}{C}+\frac{\dot{B}\dot{C}}{BC}+\frac{1}{A^2}+\frac{w}{2}\frac{\dot{\phi}^2}{\phi^2}+\left(\frac{\dot{B}}{B}+\frac{\dot{C}}{C}\right)\frac{\dot{\phi}}{\phi}+\frac{\ddot{\phi}}{\phi} = -8\pi\phi^{-1}\omega_\Lambda\rho_\Lambda \tag{10}$$

$$\frac{\ddot{A}}{A}+\frac{\ddot{C}}{C}+\frac{\dot{A}\dot{C}}{AC}-\frac{1}{A^2}+\frac{w}{2}\frac{\dot{\phi}^2}{\phi^2}+\left(\frac{\dot{A}}{A}+\frac{\dot{C}}{C}\right)\frac{\dot{\phi}}{\phi}+\frac{\ddot{\phi}}{\phi} = -8\pi\phi^{-1}(\omega_\Lambda+\delta_y)\rho_\Lambda \tag{11}$$

$$\frac{\ddot{A}}{A}+\frac{\ddot{B}}{B}+\frac{\dot{A}\dot{B}}{AB}-\frac{1}{A^2}+\frac{w}{2}\frac{\dot{\phi}^2}{\phi^2}+\left(\frac{\dot{A}}{A}+\frac{\dot{B}}{B}\right)\frac{\dot{\phi}}{\phi}+\frac{\ddot{\phi}}{\phi} = -8\pi\phi^{-1}(\omega_\Lambda+\delta_z)\rho_\Lambda \tag{12}$$

$$\frac{\dot{A}\dot{B}}{AB}+\frac{\dot{B}\dot{C}}{BC}+\frac{\dot{A}\dot{C}}{AC}-\frac{1}{A^2}-\frac{w}{2}\frac{\dot{\phi}^2}{\phi^2}+\left(\frac{\dot{A}}{A}+\frac{\dot{B}}{B}+\frac{\dot{C}}{C}\right)\frac{\dot{\phi}}{\phi} = 8\pi\phi^{-1}(\rho_m+\rho_\Lambda) \tag{13}$$

$$\frac{\dot{B}}{B}-\frac{\dot{C}}{C} = 0 \tag{14}$$

$$\ddot{\phi}+\dot{\phi}\left(\frac{\dot{A}}{A}+\frac{\dot{B}}{B}+\frac{\dot{C}}{C}\right)=\frac{8\pi}{3+2w}[\rho_\Lambda(1-3\omega_\Lambda-\delta_y-\delta_z)+\rho_m] \tag{15}$$

The conservation equation (6), yields

$$\dot{\rho_m}+\left(\frac{\dot{A}}{A}+\frac{\dot{B}}{B}+\frac{\dot{C}}{C}\right)\rho_m+\dot{\rho_\Lambda}+\left(\frac{\dot{A}}{A}+\frac{\dot{B}}{B}+\frac{\dot{C}}{C}\right)(1+\omega_\Lambda)\rho_\Lambda+\left(\delta_y\frac{\dot{B}}{B}+\delta_z\frac{\dot{C}}{C}\right)\rho_\Lambda=0, \tag{16}$$

where overhead dot stands for ordinary differentiation with respect to t.

3 Solution of the field equations

Integrating (14), we obtain

$$C = bB \tag{17}$$

where b is an integrating constant and can be taken as unity. Now if we put the value of (17) in (11) and (12), we obtain that the skewness parameters along y and z axes are equal, i.e.,

$$\delta_y = \delta_z. \tag{18}$$

Now, the field equations (10)-(15) are a system of four independent equations with seven unknown parameters ($A, B, \phi, \rho_m, \rho_\Lambda, \omega_\Lambda$ and δ_y). Three additional conditions relating these parameters are required to obtain determinate solution of the field equations.

(i). We assume that the expansion scalar (θ) is proportional to shear scalar (σ). This condition leads to ([26])

$$A = B^k \tag{19}$$

where $k \neq 1$ is a constant.

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(ii). We assume that scalar field ϕ is a function of average scale factor(a) by Johri and Kalyani [27],

$$\phi = \phi_0 a^l \tag{20}$$

where $\phi_0 > 0$ and l are arbitrary constants.

(iii). We consider the MHRDE energy density given by equation (2) in Brans-Dicke theory as

$$\rho_\Lambda = \frac{3\phi}{8\pi}(\beta_1 H^2 + \beta_2 \dot{H} + \beta_3 \ddot{H} H^{-1}), \tag{21}$$

since $M_p^2 = 1/8\pi G$ and in Brans-Dicke theory $\phi \propto G^{-1}$ ([28]).

From equations (10) and (11), we get

$$\frac{\dot{A}}{A} - \frac{\dot{B}}{B} = \frac{c_1}{V\phi} e^{\int \left(\frac{-8\pi\phi^{-1}\delta_y \rho_\Lambda + \frac{2}{A^2}}{\frac{\dot{A}}{A} - \frac{\dot{B}}{B}} \right) dt} \tag{22}$$

where $V = ABC$ is the volume of the model.
By following Adhav [29], here we consider

$$\delta_y = \frac{\phi}{8\pi\rho_\Lambda} \left(\frac{2}{A^2} + \frac{\dot{B}}{B} - \frac{\dot{A}}{A} \right) \tag{23}$$

Now from equations (19), (20) and (22), we obtain the expression for the metric coefficients

$$\begin{aligned} B &= (c_3 e^t + c_4)^{\frac{c_2}{c_4}} \\ A &= (c_3 e^t + c_4)^{\frac{kc_2}{c_4}} \end{aligned} \tag{24}$$

where $c_3 = \frac{c_1(k+2)(l+3)}{3\phi_0(1-k)}$, $c_4 = \frac{c_2(k+2)(l+3)}{3}$ and c_1, c_2 are integrating constants.
From equations (20) and (24), we get the scalar field ϕ as

$$\phi = \phi_0 (c_3 e^t + c_4)^{\frac{l}{l+3}} \tag{25}$$

Now the metric (3) can be written as

$$ds^2 = dt^2 - (c_3 e^t + c_4)^{\frac{2kc_2}{c_4}} dx^2 - (c_3 e^t + c_4)^{\frac{2c_2}{c_4}} [e^{2x} dy^2 + e^{-2x} dz^2] \tag{26}$$

From equation (2) and (24), we get the energy density of the MHRDE as

$$\rho_\Lambda = \frac{\phi_0 e^t}{24\pi (c_3 e^t + c_4)^{\frac{l+6}{l+3}}} \left(\beta_1 (k+2)^2 c_2^2 c_3^2 e^t + 3\beta_2 (k+2) c_2 c_3 - \frac{18 c_4 \beta_3}{(k+2) c_2} \right) + \frac{3\phi_0 \beta_3 c_4}{8\pi (c_3 e^t + c_4)^{\frac{3}{l+3}}} \tag{27}$$

From equations (10), (13), (23)-(25) and (27), we get
the EoS parameter of the MHRDE as

$$\omega_\Lambda = \frac{\frac{-e^t}{(c_3 e^t + c_4)^2} \left\{ 2c_2 c_3 + \frac{3 c_2^2 c_3^2 e^t}{c_4^2} + \left(\frac{\omega}{2} + 1 \right) \frac{l^2 c_3^2 e^t}{(l+3)^2} + \frac{l c_3 c_4}{l+3} + \frac{2 l c_2 c_3^2 e^t}{c_4 (l+3)} \right\} - (c_3 e^t + c_4)^{-\frac{2kc_2}{c_4}}}{\frac{e^t}{3(c_3 e^t + c_4)^2} \left(\beta_1 (k+2)^2 c_2^2 c_3^2 e^t + 3\beta_2 (k+2) c_2 c_3 - \frac{18 c_4 \beta_3}{(k+2) c_2} \right) + \frac{3\beta_3 c_4}{c_3 e^t + c_4}}, \tag{28}$$

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the energy density of the matter as

$$\rho_m = \frac{\phi_0 e^t}{8\pi(c_3e^t+c_4)^{\frac{l+6}{l+3}}}\Big\{\frac{(2k+1)e^t c_2^2c_3^2}{c_4^2} - \frac{\omega}{2}\frac{e^t l^2 c_3^2}{(l+3)^2} + \frac{le^t c_2c_3^2(k+2)}{c_4(l+3)} + \frac{\beta_1}{3}(k+2)^2c_2^2c_3^2e^t$$
$$+\beta_2(k+2)c_2c_3 - \frac{6c_4\beta_3}{(k+2)c_2}\Big\} - \frac{\phi_0}{8\pi}(c_3e^t+c_4)^{\frac{l}{l+3}-\frac{2kc_2}{c_4}} + \frac{3\phi_0\beta_3c_4}{8\pi(c_3e^t+c_4)^{\frac{3}{l+3}}}, \quad (29)$$

and the skewness parameter as

$$\delta_y = \frac{\left(\frac{2}{(c_3e^t+c_4)^{\frac{2kc_2}{c_4}}} + \frac{(1-k)c_2c_3e^t}{c_4(c_3e^t+c_4)}\right)}{\frac{e^t}{3(c_3e^t+c_4)^2}\left(\beta_1(k+2)^2c_2^2c_3^2e^t + 3\beta_2(k+2)c_2c_3 - \frac{18c_4\beta_3}{(k+2)c_2}\right) + \frac{3\beta_3c_4}{c_3e^t+c_4}} \quad (30)$$

Now the metric (26) together with equations (27)-(30) along with scalar field (25) constitutes anisotropic Bianchi type-VI_0 modified holographic Ricci dark energy model in Brans-Dicke theory of gravitation.
The overall density parameter (Ω) is

$$\begin{aligned}\Omega &= \Omega_m + \Omega_\Lambda = \frac{\rho_m+\rho_\Lambda}{3H^2}\\ &= \frac{c_2^2c_3^2(k+2)^2\phi_0e^{4t}}{8c_4^2\pi(c_3e^t+c_4)^{\frac{3(l+4)}{l+3}}}\Big\{\frac{(2k+1)c_2^2c_3^2}{c_4^2} - \frac{\omega}{2}\frac{l^2c_3^2}{(l+3)^2} + \frac{lc_2c_3^2(k+2)}{c_4(l+3)}\Big\}\\ &\qquad - \frac{c_2^2c_3^2(k+2)^2\phi_0e^{2t}}{8\pi c_4^2(c_3e^t+c_4)^{\frac{l+6}{l+3}+\frac{2kc_2}{c_4}}} \end{aligned} \quad (31)$$

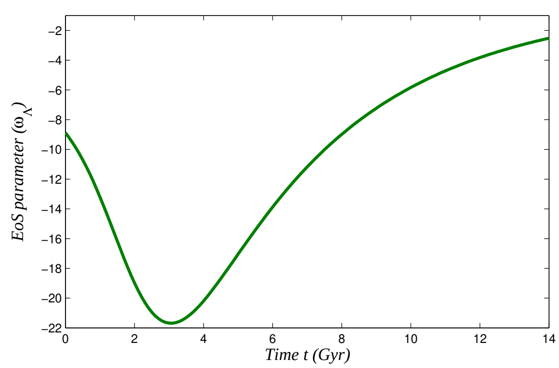

Figure 1: Plot of ω_Λ versus time t for $c_1 = c_2 = 1$, $\phi_0 = 10$, $l = 2$, $k = 0.8$, $\beta_1 = 0.2$, $\beta_2 = 1.5$, $\beta_3 = 1.6$ and $w = 2$.

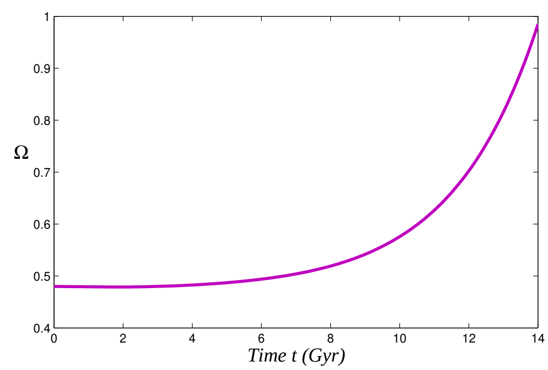

Figure 2: Plot of overall density parameter versus time t for $c_1 = c_2 = 1$, $\phi_0 = 10$, $l = 2$, $k = 0.8$, $\beta_1 = 0.2$, $\beta_2 = 1.5$, $\beta_3 = 1.6$ and $w = 2$.

We plot the EoS parameter of the MHRDE versus time (t) as shown in figure 1. It can be observed that the EoS parameter lies in the phantom ($\omega_\Lambda < -1$) region of the universe at the

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present epoch. However, it may approaches to ΛCDM model for later epoch. From figure 2, it can be observed that, the overall density parameter Ω is increases and tends to 1 at late times. That is, our model predicts a flat universe for large times ([30]). It is well known that the present day universe is very close to flat universe.

4 Some other properties of the model

Spatial volume of the model (26) is

$$V = \sqrt{-g} = (c_3 e^t + c_4)^{\frac{(k+2)c_2}{c_4}} \tag{32}$$

Average scale factor is

$$a(t) = V^{1/3} = (c_3 e^t + c_4)^{\frac{(k+2)c_2}{3c_4}} \tag{33}$$

Hubble's parameter is

$$H = \frac{\dot{a}}{a} = \frac{c_2 c_3 (k+2) e^t}{3c_4(c_3 e^t + c_4)} \tag{34}$$

Expansion scalar is

$$\theta = 3H = \frac{c_2 c_3 (k+2) e^t}{c_4(c_3 e^t + c_4)} \tag{35}$$

Shear scalar is

$$\sigma^2 = \frac{1}{3}\left(\frac{\dot{A}}{A} - \frac{\dot{B}}{B}\right)^2 = \frac{c_2^2 c_3^2 e^{2t}(k-1)^2}{c_4^2(c_3 e^t + c_4)^2} \tag{36}$$

Deceleration parameter is

$$q = \frac{-a\ddot{a}}{\dot{a}^2} = -1 - \frac{3c_4^2}{(k+2)c_2 c_3 e^t} \tag{37}$$

Average anisotropic parameter is

$$A_h = \frac{1}{3}\sum_{i=1}^{3}\left(\frac{H_i - H}{H}\right)^2 = \frac{2(k-1)^2}{(k+2)^2} \tag{38}$$

where $H_1 = \frac{\dot{A}}{A}$ and $H_2 = H_3 = \frac{\dot{B}}{B}$ are directional Hubble's parameters along x, y and z directions respectively.

In cosmology jerk parameter ($j(t)$) is used to describe models close to ΛCDM and also believed that the transition from the decelerating to the accelerating phase of the universe is due to a cosmic jerk ([31]; [32]). It is defined as the third derivative of the scale factor with respect to the cosmic time and is defined as

$$j(t) = \frac{\dddot{a}}{aH^3} = 1 - \frac{c_4}{c_2(k+2)} + \frac{9c_4^2}{c_2^2(k+2)^2}\left[1 + \frac{3c_4}{c_3 e^t} + \frac{c_4^2}{c_3^2 e^{2t}}\right]. \tag{39}$$

Figure 3, shows the behavior of deceleration parameter versus time t, from which we observe that the evolution of the universe is in accelerating phase at present era. This is in good

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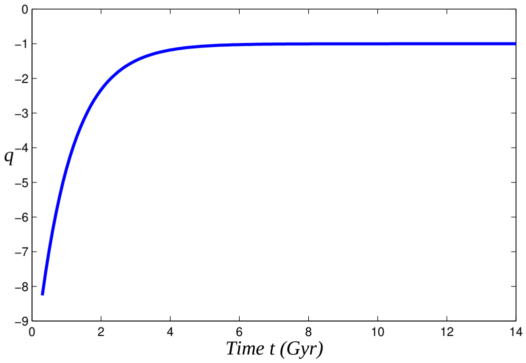

Figure 3: Plot of deceleration parameter versus time t for $c_1 = c_2 = 1$, $\phi_0 = 10$, $l = 2$ and $k = 0.8$.

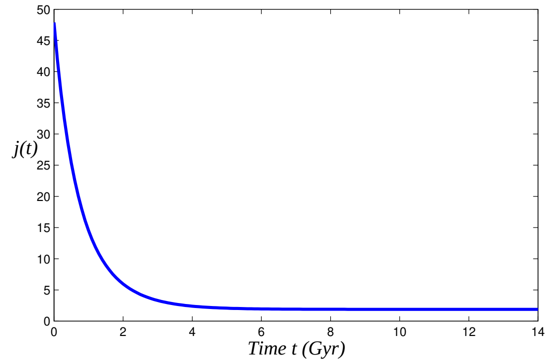

Figure 4: Plot of jerk parameter versus time t for $c_1 = c_2 = 1$, $\phi_0 = 10$, $l = 2$ and $k = 0.8$.

agreement with recent observational data that our universe is in a phase of accelerated expansion. Figure 4 describes the behavior of jerk parameter, which shows that it is positive throughout the evolution of the universe and for large values of time (t), it tends to one.

5 Conclusions

In this work, we have discussed the spatially homogeneous and anisotropic Bianchi type-VI_0 modified holographic Ricci dark energy model in Brans-Dicke scalar-tensor theory of gravitation. To obtain the deterministic model of the universe we consider some physically plausible conditions, these conditions lead to a varying deceleration parameter which represents accelerating expansion of the universe. The following are the conclusions:

It is observed that the spatial volume of the universe increases with time so that there is a exponential expansion of the universe with time. This means that we are getting an inflationary universe. The parameters H, θ and σ^2 all do not vanish at the initial epoch (i.e. at $t = 0$), and they all tend to constant value for infinite time. Also, the physical parameters do not vanish throughout the evolution of the universe. Therefore the model is free from singularities. The EoS parameter of our dark energy model favors the pilgrim dark energy ([33]) phenomenon, i.e., the phantom dark energy possesses the large negative pressure as compared to the quintessence dark energy which helps in violating the null energy condition and possibly prevent the black hole formation. The overall density parameter ($\Omega = \Omega_\Lambda + \Omega_m$) approaches close to "one" i.e., the present universe approaches towards a spatially homogeneous, isotropic and flat universe. Since the deceleration parameter is varying in negative region, our model is in accelerating phase. The cosmic jerk parameter is positive (fig. 4) throughout the entire history of the universe and for large cosmic time, the jerk parameter is tends to one. We expect the above analysis will

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definitely help to have a better insight into the understanding of dark energy in Brans-Dicke scalar-tensor theory.

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