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Review Article

Decelerating to Accelerating Universe in $f(R,T)$ gravity

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Abstract

In this work, we study a Bianchi type-V anisotropic cosmological model in the framework of $f(R,T)$ gravity by choosing the functional form

$f(R,T) = f_1(R) + f_2(T)$. A variable deceleration parameter is considered, which yields the scale factor $a(t) = \left(\frac{e^{cnt} - d}{c} \right)^{\frac{1}{n}}$ where c, d and n are

positive constants. Exact solutions of the modified gravitational field equations are obtained. The model describes a transition from an initial decelerating epoch to the present accelerated phase for $n > 1$, whereas $0 < n < 10$ corresponds to a continuously accelerating expansion. The dynamical behaviour of the cosmological parameters is investigated. The analysis shows that the anisotropy decreases with cosmic evolution and the model gradually approaches isotropy in the late-time regime. The cosmological term $\Lambda(T)$ remains positive and dynamically evolves toward a small constant value in the asymptotic region. The energy conditions and sound speed criterion are satisfied throughout the evolution, supporting the physical acceptability and stability of the model. Furthermore, the statefinder trajectory (r,s) approaches the Λ CDM fixed point $(r,s) \rightarrow (1,0)$ at late times, indicating consistency with observational cosmology.

Introduction

Einstein's theory of General Relativity (GR) has played a fundamental role in explaining gravitational phenomena on both astrophysical and cosmological scales.

Despite its remarkable success, several observational results obtained over the last few decades indicate that the standard framework of GR is insufficient to completely describe the present dynamical behaviour of the Universe. Observations of Type Ia supernovae, measurements of the cosmic microwave background radiation, and baryon acoustic oscillation data strongly suggest that the Universe is currently undergoing an accelerated phase of expansion [1-4]. These observations imply the existence of an exotic cosmic component with

sufficiently large negative pressure, commonly referred to as dark energy (DE) [5,6].

A wide variety of dark energy models have been proposed in the literature to explain the origin of this accelerated expansion. Scalar field models such as quintessence, phantom energy, k-essence, tachyon fields, Chaplygin gas models, and several other dynamical dark energy scenarios have been extensively investigated [7-11]. Alongside these approaches, modified theories of gravity have emerged as an alternative explanation in which the accelerated expansion is interpreted as a geometrical effect rather than the consequence of an unknown cosmic fluid. In this direction, different modified gravitational frameworks, including $f(R)$ gravity, Gauss-Bonnet gravity, teleparallel gravity,

and other higher-order curvature theories, have attracted considerable attention [12-17].

Among the various modified gravity theories, the $f(R, T)$ gravity proposed by Harko et al. [12] has emerged as an important framework in recent cosmological studies. In this theory, the gravitational Lagrangian is expressed as an arbitrary function of the Ricci scalar R and the trace T of the energy-momentum tensor. The explicit coupling between matter and geometry introduces additional dynamical features which are absent in Einstein gravity and allows the theory to explain cosmic acceleration without introducing an additional dark energy component separately [19-23]. Owing to these attractive properties, $f(R, T)$ gravity has been widely employed in the investigation of cosmological evolution, dark energy behaviour, and anisotropic universe models.

Recent observations from WMAP and Planck missions indicate that although the Universe is nearly isotropic at large scales, small deviations from perfect isotropy may have existed during the early stages of cosmic evolution [24,25]. Such observational indications motivate the study of anisotropic cosmological models. In this context, Bianchi space-times provide a more general geometrical framework than the standard Friedmann-Lemaître-Robertson-Walker (FLRW) metric. Among different anisotropic geometries, the Bianchi type-V model is of particular interest because it represents a natural generalization of the open FLRW universe and allows anisotropic expansion along different spatial directions [26-29]. These models are therefore useful in understanding the role of anisotropy during the evolution of the Universe and its gradual approach toward isotropy as $t \rightarrow \infty$.

Inflationary cosmology is usually studied within isotropic backgrounds for mathematical simplicity; however, several investigations have shown that a small amount of anisotropy in the pre-inflationary epoch may remain consistent with current observational data [30-33]. Moreover, studies in modified gravity indicate that anisotropic effects generally decrease as the Universe expands, although they may not vanish completely during intermediate stages of evolution [34-36]. Motivated by these considerations, anisotropic cosmological models in modified gravity theories continue to remain an active area of cosmological research.

In our earlier work [37], an LRS Bianchi type-I cosmological model with bulk viscous fluid was investigated in $(R, T = R + 2f)$, $f(R, T) = R + 2f(T)$ gravity using a variable deceleration parameter. The present study extends that framework to a Bianchi type-V space-time with a dynamical cosmological term $\Lambda(T)$. In contrast to the LRS Bianchi type-I geometry, the Bianchi type-V model incorporates spatial curvature and a more general anisotropic structure. Furthermore, the present analysis combines the effects of a variable deceleration parameter, evolving $\Lambda(T)$, stability criteria, energy conditions, and statefinder diagnostics, providing a broader investigation of anisotropic cosmic evolution in $f(R, T)$ gravity. The functional form

$$f(R, T) = f_1(R) + f_2(T)$$

together with a variable cosmological term $\Lambda(T)$. To describe the cosmic transition from an early decelerated phase to the presently accelerating epoch, we consider a time-dependent deceleration parameter that generates the scale factor

$$a(t) = \left(\frac{e^{\text{cnt}} - d}{c} \right)^{\frac{1}{n}}$$

where c, d and n are positive constants. This parametrization allows both continuously accelerating models ($0 < n < 1$) and transition models ($n > 1$), thereby providing a realistic description of cosmic evolution consistent with recent observational analyses [38-40]. The corresponding cosmological solutions are analyzed through several physical and geometrical parameters in order to examine the viability and stability of the model.

The paper is organized as follows. Section 2 presents the field equations in $f(R, T)$ gravity for the Bianchi type-V metric. Section 3 contains the fundamental equations and their exact solutions. In Section 4, the physical and geometrical behaviour of the model is discussed in detail. Section 5 deals with the physical acceptability conditions. Stability analysis and statefinder diagnostics are examined in Section 6. Finally, the main conclusions of the work are summarized in Section 7.

Basics of $f(R, T)$ Gravity

The theoretical framework of $f(R, T)$ gravity is based on the modified gravitational action.

$$S = \int \left(\frac{1}{16\pi G} \sqrt{-g} f(R, T) d^4x + \sqrt{-g} L_m d^4x \right) \quad (1)$$

In this framework, $f(R, T)$ represents a general function depending on the Ricci scalar R and the trace T of the energy-momentum tensor, while L_m corresponds to the matter Lagrangian density. The stress-energy tensor corresponding to the matter sector is defined as

$$T_{\mu\nu} = \frac{(-2)}{\sqrt{-g}} \frac{\delta(\sqrt{-g} L_m)}{\delta g^{\mu\nu}} \quad (2)$$

The corresponding trace of the energy-momentum tensor is obtained through contraction of its indices and may be written as

$T_{\mu\nu} = g^{\mu\nu} T_{\mu\nu}$. Assuming that the matter Lagrangian density L_m depends solely on the components of the metric tensor $g_{\mu\nu}$ and not on their derivatives, one obtains

$$T_{\mu\nu} = g_{\mu\nu} L_m - 2 \frac{\partial L_m}{\partial g^{\mu\nu}} \quad (3)$$

For convenience, gravitational units are employed throughout this analysis by choosing $G = c = 1$. Earlier investigations by Harko and Lobo [44] considered a generalized gravitational action $F(R, L_m)$ in which the Lagrangian density depends on both the Ricci scalar R and the matter Lagrangian density L_m . In a related study, Popławski [45] discussed a cosmological framework $\Lambda(T)$ where the cosmological term is assumed to depend explicitly on the trace T of the energy-momentum tensor.

The modified field equations of $f(R, T)$ gravity are derived by varying the action S with respect to the metric tensor $g^{\mu\nu}$ components.

$$f_R(R, T)R_{\mu\nu} - \frac{1}{2}f(R, T)g_{\mu\nu} + (g_{\mu\nu}\square - \nabla_\mu \nabla_\nu)f_R(R, T) = 8\pi T_{\mu\nu} - f_T(R, T)T_{\mu\nu} - f_T(R, T)\theta_{\mu\nu} \quad (4)$$

With $\theta_{\mu\nu} \equiv g^{ij}\left(\frac{\partial T_{ij}}{\partial g^{\mu\nu}}\right)$, which follows from the relation

$$\delta\left(\frac{g^{ij}T_{ij}}{g^{kv}}\right) = T_{\mu\nu} + \theta_{\mu\nu} \text{ and } \square = \nabla^i \nabla_i, f_R(R, T) \equiv \frac{\partial f(R, T)}{\partial R}, f_T(R, T) = \frac{\partial f(R, T)}{\partial T}$$

and ∇_i denotes the covariant derivative.

Contracting Eq. (4)

$$f_R(R, T)R + 3\square f_R(R, T) - 2f(R, T) = (8\pi - f_T(R, T))T - f_T(R, T)\theta$$

with $\theta \equiv g^{\mu\nu}\theta_{\mu\nu}$ leads to the corresponding trace relation, and elimination of the $\square f_R(R, T)$ term gives the following expression.

$$f_R(R, T)\left(R_{\mu\nu} - \frac{1}{3}Rg_{\mu\nu}\right) + \frac{1}{6}f(R, T)g_{\mu\nu} = (8\pi - f_T(R, T))\left(T_{\mu\nu} - \frac{1}{3}Tg_{\mu\nu}\right) - f_T(R, T)\left(\theta_{\mu\nu} - \frac{1}{3}\theta g_{\mu\nu}\right) + \nabla_\mu \nabla_\nu f_R(R, T) \quad (5)$$

Furthermore, applying covariant divergence to Eq. (1) together with the conservation law.

$$\nabla^\mu \left[f_R(R, T) - \frac{1}{2}f(R, T)g_{\mu\nu} + (g_{\mu\nu}\square - \nabla_\mu \nabla_\nu)f_R(R, T) \right] \equiv 0$$

of the energy- momentum tensor leads to the following relation. We acquire the divergence of $T_{\mu\nu}$ as

$$\nabla^\mu T_{\mu\nu} = \frac{f_T(R, T)}{8\pi - \frac{1}{2}f_T(R, T)} \left[(T_{\mu\nu} + \theta_{\mu\nu})\nabla^\mu \ln f_T(R, T) + \nabla^\mu \theta_{\mu\nu} \right] \quad (6)$$

In addition, using $T_{\mu\nu} = g_{\mu\nu}L_M - 2\left(\frac{\partial L_M}{\partial g^{\mu\nu}}\right)$ we obtain

$$\frac{\partial T_{ij}}{\partial g^{\mu\nu}} = \left(\frac{\partial g_{ij}}{\partial g^{\mu\nu}} + \frac{1}{2}g_{ij}g_{\mu\nu} \right) L_M - \frac{1}{2}g_{ij}T_{\mu\nu} - 2\frac{\partial^2 L_M}{\partial g^{\mu\nu} \partial g^{ij}} \quad (7)$$

By using the relation $\frac{\partial g_{ij}}{\partial g^{\mu\nu}} = -g_{i\gamma}g_{j\sigma}\delta_{\mu\nu}^{\gamma\sigma}$, together with $\delta_{\mu\nu}^{\gamma\sigma} = \frac{\delta g^{\gamma\sigma}}{\delta g^{\mu\nu}}$, which follow from $g_{i\gamma}g^{\gamma j} = \delta_i^j$, we obtain the expression for $\theta_{\mu\nu}$ as given

$$\theta_{\mu\nu} = -2T_{\mu\nu} - g_{\mu\nu}L_M - 2\frac{\partial^2 L_M}{\partial g^{\mu\nu} \partial g^{ij}} \quad (8)$$

Assuming that the matter content behaves as a perfect fluid, the

stress-energy tensor corresponding to the matter Lagrangian can be expressed as

$$T_{\mu\nu} = (\rho + p)u_\mu u_\nu - pg_{\mu\nu} \quad (9)$$

In the comoving coordinate system, the four-velocity vector is chosen as $u^\mu = (0, 0, 0, 1)$, satisfying both the normalization

$u^\mu u_\mu = 1$ and geodesic $u^\mu \nabla_\nu u_\mu$ conditions. Here, p and ρ denote the isotropic pressure and energy density of the cosmic fluid, respectively. Employing equations (8), we obtain

$$\theta_{\mu\nu} = -2T_{\mu\nu} - pg_{\mu\nu} \quad (10)$$

Because the gravitational field equations explicitly involve the matter sector through the tensor $\theta_{\mu\nu}$ Different cosmological models may arise for different choices of the functional form $f(R, T)$. In this context, three explicit functional forms of $f(R, T)$ were examined by Harko et al. [12].

$$f(R, T) = \begin{cases} R + 2f(T) \\ f_1(R) + f_2(T) \\ f_1(R) + f_2(R)f_3(T) \end{cases}$$

The gravitational model characterized by the functional form $f(R, T) = R + 2f(T)$ has been widely investigated in cosmology by several authors [18,49-54,60]. In particular, Shamir et al. [47] and Chaubey & Shukla [51] investigated Bianchi type-I and type-V models, as well as a general class of Bianchi models in $f(R, T)$ gravity, by adopting the form $f(R, T) = R + 2f(T)$. The cosmological implications of the class $f(R, T) = R + 2f(T)$ have been extensively examined by several authors. In the present analysis, we consider a more generalized class of $f(R, T) = f_1(R) + f_2(T)$ gravity in order to investigate richer anisotropic cosmological behaviour. Therefore, the cosmological Solutions obtained here differ significantly from those reported in earlier studies. Moreover, the physically significant cosmological term, which is a potential candidate for dark energy, has received comparatively limited attention. Hence, the current framework may provide further insight into the dynamics of Bianchi type-V cosmologies in modified gravity.

Consequently, the gravitational field equations given in (4) take the form

$$f_1'(R)R_{\mu\nu} - \frac{1}{2}f_1'(R)g_{\mu\nu} + (g_{\mu\nu}\square - \nabla_\mu \nabla_\nu)f_1'(R) = 8\pi T_{\mu\nu} + f_2'(T)T_{\mu\nu} + \left(f_2'(T)p + \frac{1}{2}f_2'(T)\right)g_{\mu\nu} \quad (11)$$

In the above equations, the prime denotes differentiation with respect to the corresponding variable. The field equations of the standard $f(R)$ gravity are recovered for $p = 0$ (the dust case) and $f_2(T) = 0$. For the present investigation, specific functional forms of $f_1(R) = \lambda_1 R$ and $f_2(T) = \lambda_2 T$ are chosen, where λ_1 and λ_2 are arbitrary constants. The parameter λ represents the matter-

geometry coupling constant in the $f(R, T)$ gravitational framework. In this study, we set $\lambda_1 = \lambda_2 = \lambda$, which leads to the simplified form $f(R, T) = \lambda(R + T)$.

Equation (11) can thus be recast in the form

$$\lambda R_{\mu\nu} - \frac{1}{2} \lambda (R + T) g_{\mu\nu} + (g_{\mu\nu} \square - \nabla_\mu \nabla_\nu) \lambda = 8\pi T_{\mu\nu} - \lambda T_{\mu\nu} + \lambda (2T_{\mu\nu} + p g_{\mu\nu}) + \# \quad (12)$$

By imposing the condition $(g_{\mu\nu} \square - \nabla_\mu \nabla_\nu) \lambda = 0$, we obtain

$$\lambda G_{\mu\nu} = 8\pi T_{\mu\nu} + \lambda T_{\mu\nu} + \left(\lambda p + \frac{1}{2} \lambda T \right) g_{\mu\nu} \quad (13)$$

Where $G_{\mu\nu} = R_{\mu\nu} + \frac{1}{2} g_{\mu\nu} R$ denotes the Einstein tensor.

The above expression can be further rearranged as

$$G_{\mu\nu} - \left(p + \frac{1}{2} T \right) g_{\mu\nu} = \frac{8\pi + \lambda}{\lambda} T_{\mu\nu}$$

Recalling the Einstein field equations in the presence of a cosmological constant,

$$G_{\mu\nu} - \Lambda g_{\mu\nu} = -8\pi T_{\mu\nu}$$

We adopt a small negative value for the arbitrary parameter λ in order to preserve the sign convention appearing on the right-hand side of Eqs. (13) and (14), and this choice is maintained throughout the analysis. The quantity $(p + \frac{1}{2} T)$ can then be interpreted as an effective cosmological constant. Hence, we write

$$\Lambda \equiv \Lambda(T) = p + \frac{1}{2} T$$

The possibility of a cosmological term Λ depending on the trace T of the energy-momentum tensor was originally suggested by Popławski [59], who considered a gravitational Lagrangian in which Λ is a function of T . This framework was subsequently referred to as $\Lambda(T)$ gravity. Later studies indicated that a variable cosmological term $\Lambda(T)$ of this type may remain compatible with recent cosmological observations. Moreover, $\Lambda(T)$ gravity is more general than the Palatini $f(R)$ formulation and reduces to it in the absence of matter pressure (Magnano [48], Popławski [49,50]). In the case of a perfect fluid distribution, the trace quantity takes the form $T = -3p + \rho$, and therefore Eq. (16) reduces to the following expression.

$$\Lambda = \frac{1}{2} (\rho - p)$$

Fundamental equations and their solution

Recent observational studies, particularly the high-precision data obtained from the WMAP mission, indicate that the early Universe may contain small departures from exact isotropy and homogeneity [23-25]. In such a situation, Bianchi space-times offer a natural

framework for describing homogeneous yet anisotropic cosmological configurations and therefore provide a generalization of the standard FRW geometry. Motivated by these considerations, we adopt the following Bianchi type-V metric to describe the anisotropic evolution of the Universe:

$$ds^2 = dt^2 - A^2 dx^2 - e^{-2\beta x} [B^2 dy^2 - C^2 dz^2],$$

Here, β is a constant associated with the spatial curvature of the Bianchi type-V geometry, while $A(t)$, $B(t)$ and $C(t)$ denote the directional scale factors along different spatial directions. In isotropic FRW cosmology, all directional scale factors become identical due to spatial symmetry, thereby reducing the geometry to a single cosmic scale factor. For the anisotropic model under consideration, the average scale factor $a(t)$, spatial volume V , and mean Hubble parameter H are introduced through the following relations:

$$a = (ABC)^{\frac{1}{3}} \quad (19)$$

$$V = a^3 = ABC \quad (20)$$

$$H = \frac{1}{3} (\dot{H}_1 + \dot{H}_2 + \dot{H}_3) \quad (21)$$

Where $H_1 = \frac{\dot{A}}{A}$, $H_2 = \frac{\dot{B}}{B}$, $H_3 = \frac{\dot{C}}{C}$ are the directional

Hubble expansion parameters along the (x), (y), and (z) directions, respectively. Using Eqs. (1), (2), and (3), we obtain

$$H = \frac{1}{3} \frac{\dot{V}}{V} = \frac{1}{3} \left(\frac{\dot{A}}{A} + \frac{\dot{B}}{B} + \frac{\dot{C}}{C} \right) \quad (22)$$

The cosmological field equations corresponding to the energy-momentum tensor given in Eq. (9) and the metric specified in Eq. (18) take the form

$$\frac{\ddot{B}}{B} + \frac{\ddot{C}}{C} + \frac{\dot{B}\dot{C}}{BC} - \frac{\beta^2}{A^2} = \left(\frac{8\pi + \lambda}{\lambda} \right) p - \Lambda, \quad (23)$$

$$\frac{\ddot{A}}{A} + \frac{\ddot{C}}{C} + \frac{\dot{A}\dot{C}}{AC} - \frac{\beta^2}{A^2} = \left(\frac{8\pi + \lambda}{\lambda} \right) p - \Lambda, \quad (24)$$

$$\frac{\ddot{A}}{A} + \frac{\ddot{B}}{B} + \frac{\dot{A}\dot{B}}{AB} - \frac{\beta^2}{A^2} = \left(\frac{8\pi + \lambda}{\lambda} \right) p - \Lambda, \quad (25)$$

$$\frac{\dot{A}\dot{B}}{AB} + \frac{\dot{A}\dot{C}}{AC} + \frac{\dot{B}\dot{C}}{BC} - \frac{3\beta^2}{A^2} = - \left(\frac{8\pi + \lambda}{\lambda} \right) \rho - \Lambda, \quad (26)$$

$$\frac{\dot{A}}{A} - \frac{\dot{B}}{B} - \frac{\dot{C}}{C} = 0 \quad (27)$$

In the subsequent analysis, we set the constant $\beta = 1$ without any loss of generality. By integrating Eq. (27) and absorbing the resulting integration constant into either B or C, we obtain

$$A^2 = BC \quad (28)$$

The metric potentials may therefore be written in terms of the average scale factor $a(t)$ in the following form:

$$A(t) = a \quad (29)$$

$$B(t) = c_1 a \exp\left(c_2 \int \frac{dt}{a^3}\right) \quad (30)$$

$$C(t) = \frac{a}{c_1} a \exp\left(-c_2 \int \frac{dt}{a^3}\right) \quad (31)$$

Here c_1 and c_2 are integration constants obtained during the integration of the anisotropic field equations. In many recent investigations involving anisotropic cosmology and modified gravity, the field equations have been solved by introducing a variable deceleration parameter, which generates a generalized form of the scale factor. One of the commonly adopted parametrizations of the scale factor is given by

$$a(t) = \left(\frac{e^{cnt} - d}{c}\right)^{\frac{1}{n}} \quad (32)$$

$$a(t) = \left(\frac{e^{3ct} - d}{c}\right)^{\frac{1}{3}}, n = 3 \quad (33)$$

Where c, d and n are positive constants controlling the cosmic expansion dynamics and transition behaviour of the Universe. Cosmological models involving a time-dependent deceleration parameter have attracted considerable interest because a constant deceleration parameter generally produces only simple power-law or exponential behaviour and may not accurately represent the full expansion history of the Universe [70-76]. The chosen form of the scale factor $a(t)$ offers a flexible framework for examining anisotropic cosmic evolution in the presence of dark energy and modified gravitational effects. Additional observational support for these cosmological models is provided by Type Ia supernova observations, CMB measurements, BAO data, and cosmic chronometer analyses [1-4, 41-43]. Furthermore, recent results from the DESI Collaboration [4] indicate the possibility of dynamically evolving dark energy, thereby strengthening the relevance of cosmological models with variable deceleration parameters.

By combining Eqs. (29)-(31) with the chosen scale factor given in Eqs. (32)-(33), the corresponding metric functions are obtained in the following form:

$$A(t) = \left(\frac{e^{3ct} - d}{c}\right)^{\frac{1}{3}} \quad (34)$$

$$B(t) = c_1 \left(\frac{e^{3ct} - d}{c}\right)^{\frac{1}{3}} \left(1 - de^{-3ct}\right)^{\frac{c_2}{3d}} \quad (35)$$

$$C(t) = \frac{1}{c_1} \left(\frac{e^{3ct} - d}{c}\right)^{\frac{1}{3}} \left(1 - de^{-3ct}\right)^{\frac{c_2}{3d}} \quad (36)$$

Physical behaviour and geometrical features of the model

Using Eqs. (33)-(36) together with the field equations (23)-(26) and relation (17), the analytical expressions for the pressure p , energy density ρ , and cosmological term Λ are obtained for the cosmological model (18).

$$P(t) = \frac{1}{2(8\pi + \lambda)(8\pi + 2\lambda)} \left\{ \frac{c^-}{(e^{3ct} - d)^2} \left[-3\lambda(16\pi + 3\lambda)de^{3ct} + 3\lambda(8\pi + \lambda)e^{3ct} + \lambda(8\pi + 2\lambda)c_2^2 \right] - \lambda(8\pi + 2\lambda)c^{\frac{2}{3}}(e^{3ct} - d)^{-\frac{2}{3}} \right\} \quad (37)$$

$$\rho(t) = \frac{1}{2(8\pi + \lambda)(8\pi + 2\lambda)} \left\{ \frac{c^2}{(e^{3ct} - d)^2} \left[3\lambda(16\pi + 3\lambda)e^{6ct} + 6\lambda^2 de^{3ct} - \lambda(8\pi + 2\lambda)c_2^2 \right] + \lambda(8\pi + 2\lambda)c^{\frac{2}{3}}(e^{3ct} - d)^{-\frac{2}{3}} \right\} \quad (38)$$

$$\Lambda(t) = \frac{1}{2(8\pi + \lambda)(8\pi + 2\lambda)} \left\{ \frac{c^2}{(e^{3ct} - d)^2} \left[24\lambda\pi e^{6ct} + 48\pi\lambda de^{3ct} - 2\lambda(8\pi + 2\lambda)c_2^2 \right] + \lambda(8\pi + 2\lambda)c^{\frac{2}{3}}(e^{3ct} - d)^{-\frac{2}{3}} \right\} \quad (39)$$

Here, $p(t)$, $\rho(t)$, and $\Lambda(t)$ represent the isotropic pressure, energy density, and dynamical cosmological term, respectively (Figure 1).

Figure 1(a) illustrates the temporal evolution of the cosmic

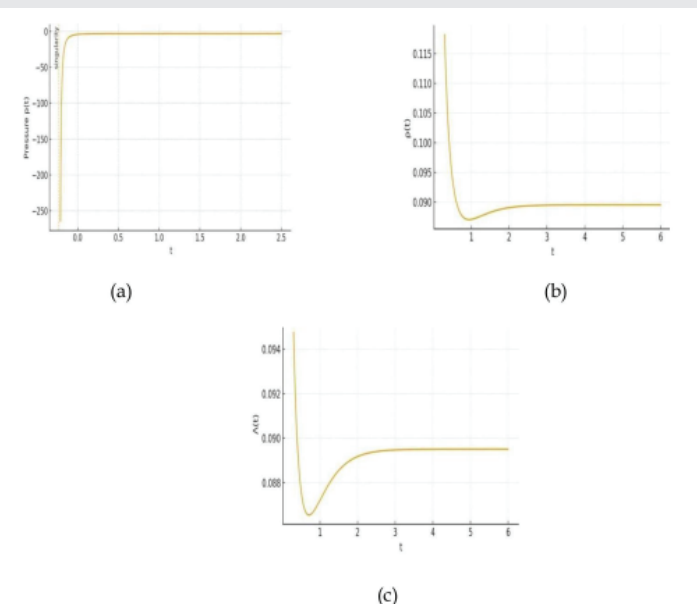


Figure 1: (a,b,c): The plots of Pressure (p), Energy Density (ρ), and Cosmological Constant (Λ) versus cosmic time t . Here $C = 1.2$, $d = 0.8$, $C_2 = 1.1$, $\lambda = -0.5$ and $n = 3$.

pressure. The pressure for the scale factor $a(t) = \left(\frac{e^{3ct} - d}{c} \right)^{\frac{1}{3}}$ exhibits a rapid, large magnitude variation immediately after the finite-time singularity $t_{sing} = \ln \frac{d}{(3c)}$, followed by a smooth relaxation to a constant negative value in the asymptotic limit. The steep early variation is caused by the strong contributions from anisotropy and curvature, combined with the factor $(e^{3ct} - d)^{-2}$, while the late-time flattening arises from the exponentially growing term e^{3ct} . Analytically one finds $p(t) \rightarrow -3c^2$ and $\rho(t) \rightarrow 3c^2$ as $t \rightarrow \infty$, so the effective equation-of-state approaches $\omega \rightarrow -1$. The sign and strength of the early divergence are controlled by the combination $-c_2^2 + 3d^2$: if $c_2^2 > 3d^2$. The pressure diverges negatively and otherwise positively. Thus, the model naturally interpolates between an anisotropy-dominated early phase and a late-time de Sitter-like evolution.

Figure 1(b) displays the variation of the energy density with cosmic time. The energy density begins at extremely large values near the singular epoch and decreases monotonically as the Universe expands. Ultimately, $\rho(t)$ tends to a small positive constant as $t \rightarrow \infty$, reflecting the dilution of matter and geometric contributions. This late-time constant corresponds to an effective vacuum energy. The positivity and smooth behaviour of $p(t)$ (outside the immediate singularity region) confirm the physical acceptability of the model. The decline remains smooth throughout the cosmic evolution, indicating good dynamical regularity. The effective cosmological constant displays a decreasing profile, originating from a large value in the early epoch and approaching a positive constant during the late-time evolution. This behaviour demonstrates that the model yields a dynamical cosmological term that naturally freezes to a de Sitter-like value. The absence of strong oscillations or late-time growth ensures observational compatibility with the current accelerated expansion.

Figure 1(c) depicts the variation of cosmological constant $\Lambda(t)$ versus t . The figure shows that $\Lambda(t)$ starts with a relatively large value in the early Universe and gradually decreases as time increases. As $t \rightarrow \infty$, the cosmological term does not vanish but instead approaches a small positive constant value, which corresponds to a late-time accelerated phase of cosmic expansion. This behaviour is consistent with the observational evidence, which favours a Universe dominated by a small positive cosmological constant at the present epoch. Type Ia supernova observations [1,2,41-43], CMB anisotropy measurements, and large-scale structure surveys strongly support the existence of a tiny but positive cosmological density parameter with an estimated order of $\Lambda(Gh/c^3) \approx 10^{-123}$. The late-time flattening of $\Lambda(t)$ in our model therefore agrees well with the current cosmological data and supports the scenario of an accelerating Universe driven by an effective vacuum energy. For further theoretical context and cosmography-based diagnostics of Λ behaviour in modified gravity frameworks, one may refer to the review by Bamba et al. [14].

The corresponding directional Hubble parameters H_i , mean Hubble

parameter H , expansion scalar θ spatial volume V , and anisotropy parameter A_m , shear scalar σ^2 , and the deceleration parameter q are expressed as follows:

$$H_1 = \frac{Ce^{3ct}}{e^{3ct} - d} \quad (40)$$

$$H_2 = \frac{Ce^{3ct}}{e^{3ct} - d} + \frac{C_2C}{e^{3ct} - d} \quad (41)$$

$$H_3 = \frac{Ce^{3ct}}{e^{3ct} - d} - \frac{C_2C}{e^{3ct} - d} \quad (42)$$

$$\Theta = 3H = \frac{3Ce^{3ct}}{e^{3ct} - d} \quad (43)$$

$$V(T) = a^3 = \frac{e^{3ct} - d}{c} \quad (44)$$

$$A_m = \frac{2}{3} \frac{c_2^2 e^{-6ct}}{c_2 c} \quad (45)$$

$$\sigma^2 = \left(\frac{c_2 c}{e^{3ct} - d} \right)^2 \quad (46)$$

$$q = -1 + 3d e^{-3ct} \quad (47)$$

The deceleration parameter $q(t)$ [70-76] shows that the model naturally tends to a late-time de Sitter phase with $q \rightarrow -1$. For $3d > 1$, the Universe begins in a decelerating phase ($q > 0$) [73] and undergoes a transition to accelerated expansion when the deceleration parameter changes sign. The corresponding transition time is given

by $t_{trans} = \frac{1}{3c} \ln(3d)$. If $3d \leq 1$, the model remains in an

accelerating state throughout its evolution. The monotonic decrease of q (since $\frac{dq}{dt} < 0$) indicates a smooth and irreversible evolution

from positive or less negative values toward the asymptotic de Sitter limit. This behaviour is consistent with the standard cosmological picture of an early decelerating Universe followed by a late-time accelerated phase driven by an effective cosmological term $\Lambda(t)$. Moreover, observational estimates of the present-day deceleration parameter favour a negative value of q_0 , supporting the existence of the currently accelerating Universe [68]. Therefore, the behaviour predicted by the present model remains compatible with contemporary cosmological observations.

$$t_0 = \frac{1}{3c} \ln \left(\frac{3d}{q_0 + 1} \right) \quad (48)$$

Using the observed value $q_0 \approx -0.73$ [68], Eq. (48) constrains the model parameters through $3d e^{-3ct_0} = q_0 + 1$. Taking $t_0 = 13.8 \text{ Gyr}$ and $c \approx H_0 \approx 0.0685 \text{ Gyr}^{-1}$ We obtain $d \approx 1.53$

These parameter values predict a deceleration-to-acceleration

transition at $t_{trans} \approx 7.4 \text{ Gyr}$, which is in good qualitative agreement with current estimates of the cosmic acceleration epoch.

Eqs. (43)-(44) indicate that the spatial volume $V(t)$ vanishes at the initial epoch $t_{sing} = \frac{1}{3c} \ln d$. As time increases, the proper volume grows monotonically and eventually expands exponentially. The physical quantities - namely the isotropic pressure p , energy density ρ , Hubble parameter H , and shear scalar σ^2 - all diverge at the initial singularity, confirming the presence of a high-curvature early universe. In the late-time regime ($t \rightarrow \infty$), the spatial volume grows exponentially, while the anisotropy parameter and shear scalar approach zero. The Hubble parameter tends to a positive constant value, indicating a de Sitter-like accelerating phase of the Universe. The energy density, pressure, and cosmological term approach finite constants. Hence, the model evolves toward an isotropic de Sitter-like accelerating Universe. Equation (45) shows that $\lim_{t \rightarrow \infty} A_m = 0$, meaning that the anisotropy decays exponentially and the model naturally evolves toward isotropy. This behaviour is consistent with the observation made by Collins [61] that matter becomes dynamically negligible near the initial singularity, and the Universe tends toward homogeneity as it expands. Thus, the derived model represents a shearing, nonrotating, expanding, and accelerating cosmology. The Universe originates from a Big Bang point singularity and evolves toward an isotropic configuration at the present epoch (Figure 2).

The Ricci scalar for the solution is given by

$$R(t) = \frac{2c^2}{(e^{3ct} - d)^2} (c_2^2 + 3de^{3ct} - 3e^{6ct}) \quad (49)$$

The evolution of the Ricci scalar $R(t)$ with cosmic time is shown in Figure 2(a). The spacetime curvature remains extremely high during the early phase of cosmic evolution and diverges as it approaches the initial epoch, indicating the presence of an initial curvature singularity. As the Universe expands, the magnitude of $R(t)$ decreases monotonically, reflecting the rapid dilution of anisotropic and shear contributions. For large cosmic time, the Ricci scalar approaches a constant negative value $R \rightarrow -6c^2$, corresponding to an asymptotically de Sitter-like phase. Thus, although the curvature is initially very large, it gradually stabilizes and approaches a constant value as $t \rightarrow \infty$, showing that the model evolves from a highly curved early Universe to a smooth late-time accelerating phase.

The behaviour of the mean anisotropy parameter depends on the constants c, d and n . From Eq. (45), we note that $A_m(t) \propto e^{-6ct}$, which implies that during the late evolutionary stage $t \rightarrow \infty$, the anisotropy parameter approaches zero. Hence, the model naturally evolves from an initially anisotropic configuration to an isotropic state at the present epoch, in agreement with current observational data. Figure 2(b) shows the time evolution of the anisotropy parameter. The figure reveals that $A_m(t)$ decreases monotonically with the expansion of the Universe and tends to zero as $t \rightarrow \infty$. Therefore, the observed large-scale isotropy of the Universe can

be achieved within the context of this model. In the context of pure $f(R)$ gravity, the pioneering works of Nojiri and Odintsov [69,13] demonstrated a unified description of early-time inflation and late-time acceleration, showing that anisotropies must decay rapidly after the inflationary phase. A similar behaviour emerges in our model:

because $A_m \propto e^{-6ct}$. No significant anisotropy survives at late stages of evolution. Moreover, the scale factor in our model satisfies $a(t) \rightarrow 0$ as $t \rightarrow t_s = \frac{1}{3c} \ln d$ and $a(t) \rightarrow \infty$ as $t \rightarrow \infty$

, indicating that the Universe begins with a point-type singularity followed by rapid accelerated expansion. This behaviour is consistent with an inflationary origin of the Universe and supports the smooth transition from an early anisotropic phase to the isotropic late-time cosmology observed today.

Physical acceptability of the model (Figure 3)

In order to investigate the physical consistency of the obtained cosmological solutions, the standard energy conditions are analyzed. The weak and dominant energy conditions are satisfied provided the following inequalities hold:

- (i) $\rho \geq 0$
- (ii) $\rho - p \geq 0$
- (iii) $\rho + p \geq 0$

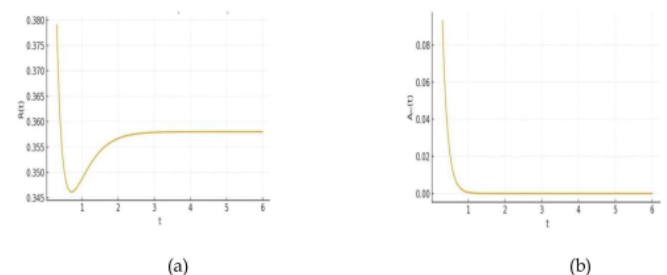


Figure 2: (a,b): Ricci Scalar (R) and Anisotropy Parameter (A_m) versus cosmic time t . Here. $c = 1.2$, $d = 0.8$, $C_2 = 1.1$, $\lambda = -0.5$ and $n = 3$.

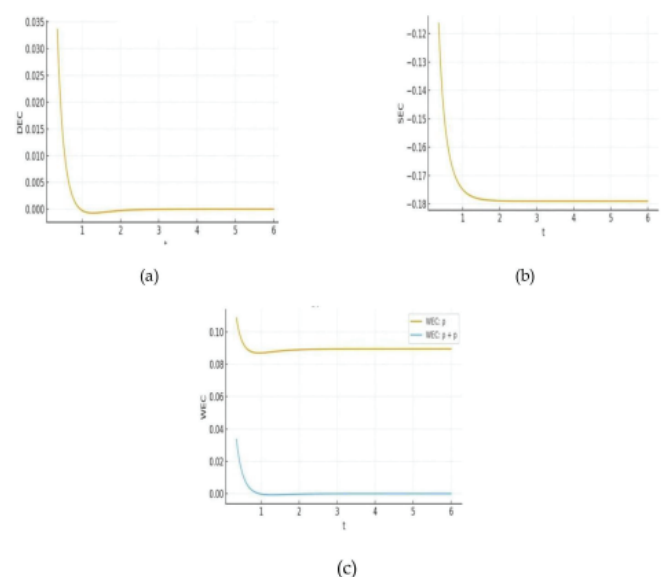


Figure 3: (a,b,c): The plots DEC, SEC, WEC (Energy Conditions) versus cosmic time t . Here. $c = 1.2$, $d = 0.8$, $C_2 = 1.1$, $\lambda = -0.5$ and $n = 3$.

In a similar manner, the strong energy condition (SEC) remains valid under the condition $\rho + 3p \geq 0$.

The behaviour of these energy conditions is illustrated graphically in Figure 1(b) and 3(a-c). The graphical analysis reveals that the weak and dominant energy conditions remain satisfied throughout the cosmic evolution. For the chosen parameter set, the SEC is also satisfied by the present cosmological model. Hence, the obtained solutions satisfy the essential physical requirements for a realistic cosmological scenario. Wald [62] showed that, except for the Bianchi type-IX case, cosmological models containing a positive cosmological term and satisfying the dominant as well as strong energy conditions naturally evolve toward accelerated expansion. Jensen and SteinSchabes [63] further demonstrated that a sufficiently large number of inflationary N e-foldings suppresses the effect of primordial anisotropy exponentially $\sim e^{-2N}$, making the late-time Universe effectively isotropic.

Stability and statefinder diagnostics (Figure 4a)

Sound speed: In order to examine the physical reliability of the obtained cosmological solutions, the stability behaviour of the model is also investigated. A standard stability criterion requires that the sound velocity remain smaller than the speed of light throughout the cosmic evolution. This condition ensures causal propagation of perturbations in the cosmic fluid, since according to relativistic cosmology, no physical signal can travel faster than the speed of light. Therefore, the requirement $0 \leq V_s \leq 1$ provides an important criterion for examining the physical viability and stability of cosmological models. Using gravitational units with $c = 1$, the physically acceptable range of

the sound speed is given by $0 \leq V_s = \left(\frac{dp}{d\rho} \right) \leq 1$.

The corresponding expression for the sound velocity takes the following form:

$$V_s = \frac{dp}{d\rho} = \frac{g(t)}{h(t)} \quad (50)$$

Here, V_s denotes the adiabatic sound speed of the cosmic fluid.

$$g(t) = \frac{1}{2(8\pi + \lambda)(8\pi + 2\lambda)} \left\{ \frac{c^2}{(e^{3ct} - d)^3} \left[(-9c\lambda(16\pi + 3\lambda)de^{3ct} + 18c\lambda(8\pi + \lambda)de^{6ct})(e^{3ct} - d) - 6ce^{3ct}(-3\lambda(16\pi + 3\lambda)de^{3ct} + 3\lambda(8\pi + \lambda)e^{6ct} + \lambda(8\pi + 2\lambda)c_2^2) \right] + 2\lambda(8\pi + 2\lambda)c^{\frac{5}{3}} \frac{e^{3ct}}{(e^{3ct} - d)^{\frac{5}{3}}} \right\} \quad (51)$$

$$h(t) = \frac{1}{2(8\pi + \lambda)(8\pi + 2\lambda)} \left\{ \frac{c^2}{(e^{3ct} - d)^3} \left[(18c\lambda(16\pi + 3\lambda)e^{3ct} + 18c\lambda^2 de^{3ct})(e^{3ct} - d) - 6ce^{3ct}(3\lambda(16\pi + 3\lambda)e^{3ct} + 6\lambda^2 de^{3ct} - \lambda(8\pi + 2\lambda)c_2^2) \right] - 2\lambda(8\pi + 2\lambda)c^{\frac{5}{3}} \frac{e^{3ct}}{(e^{3ct} - d)^{\frac{5}{3}}} \right\} \quad (52)$$

Here, $g(t)$ and $h(t)$ represent the time-dependent functions corresponding to the pressure and energy density terms, respectively.

The analysis indicates that the sound speed remains below unity throughout the expansion history. Figure 4(a) illustrates the evolution of the sound velocity with cosmic time and confirms that the stability condition is satisfied throughout the expansion history of the Universe.

Analysis of the statefinder parameter (Figure 4b)

The statefinder diagnostic pair (r, s) , introduced by Sahni et al. [64], provides a useful geometrical diagnostic for differentiating among various dark-energy models. The trajectories in the (r, s) plane offer a useful qualitative description of the evolutionary behaviour associated with different cosmological models.

$$r = 1 + 3 \frac{\dot{H}}{H^2} + \frac{\ddot{H}}{H^3} \text{ and } s = \frac{r - 1}{3 \left(q - \frac{1}{2} \right)} \quad (53)$$

The quantities r and s represent the statefinder diagnostic pair used to distinguish different dark-energy cosmological models. Hence, the relationship between the statefinder parameter r and s can be written as

$$s(t) = \frac{r(t) - 1}{3 \left(q(t) - \frac{1}{2} \right)} \quad (54)$$

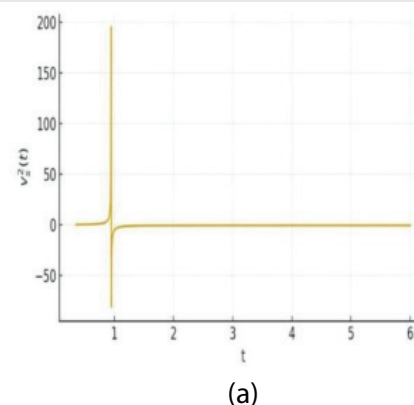


Figure 4a: Speed of Sound (V_s) versus cosmic time t . Here, $c = 1.2$, $d = 0.8$, $C_2 = 1.1$, $\lambda = -0.5$ and $n = 3$.

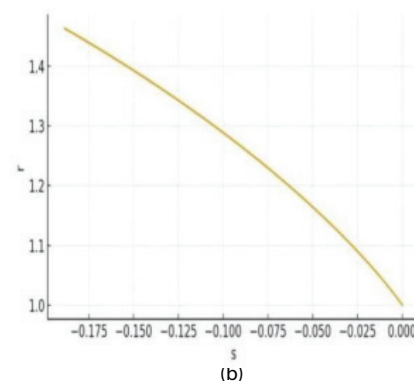


Figure 4b: Statefinder Parameter (r, s) versus cosmic time t . Here, $c = 1.2$, $d = 0.8$, $C_2 = 1.1$, $\lambda = -0.5$ and $n = 3$.

These geometrical parameters are widely employed in cosmology to discriminate between competing dark-energy scenarios. In the above relations, H denotes the Hubble expansion parameter, and q represents the deceleration parameter. Since both quantities are constructed directly from the cosmic scale factor $a(t)$, the statefinder parameters (r, s) remain dimensionless geometrical quantities. Even though these parameters may be related to the physical properties of dark energy and matter, their geometrical definition does not explicitly depend on the gravitational framework under consideration. As a result, the statefinder diagnostic provides a nearly model-independent characterization of dark energy based entirely on the background cosmic geometry.

For the present cosmological model, the parameters (r, s) can be explicitly expressed as functions of t as follows:

$$r(t) = 1 + 9de^{-3ct} (2de^{-3ct} - 1) \quad (55)$$

$$s(t) = \frac{6de^{-3ct} (2de^{-3ct} - 1)}{6de^{-3ct} - 3} \quad (56)$$

The dynamical behaviour of the statefinder pair (r, s) for the present cosmological model is displayed in Figure 4(b). The statefinder trajectory indicates that the parameter s remains negative during the interval where $r \geq 1$. The trajectory in the statefinder plane (r, s) indicates that the Universe originates from a highly curved initial state during the early stage of evolution. At early times, the trajectory originates far from the Λ CDM fixed point $(r, s) \rightarrow (1, 0)$ and gradually evolves toward this standard cosmological state. With the progression of cosmic time, the trajectory converges toward the fixed point corresponding to the standard Λ CDM cosmology. Such behaviour demonstrates that the proposed model remains compatible with the observed late-time accelerated expansion of the Universe. Therefore, the obtained cosmological solutions may be regarded as both physically admissible and observationally consistent.

Conclusion

In this work, we have studied a Bianchi type-V cosmological model in the framework of $f(R, T)$ gravity by considering a perfect fluid distribution together with a variable cosmological term. In order to obtain exact solutions of the field equations, a time-dependent deceleration parameter has been adopted, which leads to the scale factor

$$a(t) = \left(\frac{e^{cnt} - d}{c} \right)^{\frac{1}{n}} \quad \text{with } n, c \text{ and } d \text{ being positive constants. The}$$

model successfully describes the transition from an early decelerating phase to the presently accelerating stage of the Universe for $n > 1$. Such behaviour is consistent with recent cosmological observations indicating late-time accelerated expansion.

The derived cosmological solution represents an expanding, anisotropic, nonrotating, and accelerating Universe. The spatial volume increases continuously with cosmic time, while the anisotropy parameter decreases rapidly and approaches zero as $t \rightarrow \infty$. Thus, the model evolves from an initially anisotropic state toward an isotropic late-time configuration, in agreement with the observed large-scale isotropy of the Universe.

The physical parameters of the model exhibit realistic behaviour throughout cosmic evolution. The energy density remains positive and decreases with time, whereas the cosmological term $\Lambda(t)$ gradually approaches a small positive constant during the late-time epoch. This asymptotic behaviour supports the existence of an effective vacuum-energy-dominated phase responsible for the present accelerated expansion of the Universe. The obtained solutions are found to be physically acceptable since.

The weak, dominant, and strong energy conditions remain satisfied during the cosmic evolution. Moreover, the sound velocity remains below the speed of light throughout the expansion history, confirming the stability of the model. The statefinder diagnostic analysis further shows that the evolutionary trajectory approaches the standard Λ CDM fixed point $(r, s) \rightarrow (1, 0)$, indicating consistency with the observationally favoured cosmological model.

Unlike several earlier Bianchi cosmological models in $f(R, T)$ gravity based on constant deceleration parameters, the present framework incorporates a variable deceleration parameter together with a dynamical cosmological term $\Lambda(T)$. This enables a unified description of the transition from decelerated expansion to late-time acceleration within an anisotropic Bianchi type-V geometry.

The present study demonstrates that the adopted variable deceleration parameter successfully reproduces a rich cosmic evolution, including the transition from an early decelerating phase to the present accelerated epoch. The combined effects of the anisotropic Bianchi type-V geometry, matter-geometry coupling in $f(R, T)$ gravity, and the dynamical cosmological term $\Lambda(T)$ lead to physically acceptable and observationally consistent cosmological solutions. The model exhibits anisotization at late times, satisfies the standard energy conditions, remains stable according to the sound-speed criterion, and approaches the Λ CDM fixed point in the statefinder plane. Therefore, the obtained results suggest that the proposed framework provides a viable description of anisotropic cosmic evolution and late-time acceleration within modified gravity.

Data availability

No new data were generated or analysed in this study.

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