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AXIALLY SYMMETRIC COSMOLOGICAL MODEL IN $f(Q,T)$ GRAVITY

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This article is devoted to the study of the dynamical aspects of the domain wall cosmological model in an axially symmetric space-time in $f(Q,T)$ gravity. In this theory of gravity, the action contains an arbitrary function $f(Q,T)$ where Q and T respectively denote the non-metricity and the trace of the energy-momentum tensor. The linear and additive form of $f(Q,T)$ gravity, $f(Q,T) = \mu Q + \nu T$ where μ and ν are non-zero arbitrary constants, is taken into account in this work. A deterministic model of the universe is obtained using the linearly varying deceleration parameter $q = -kt + m - 1$ which is linear in time with negative slope. We have assessed all the dynamical and geometrical parameters of the models and examined their physical significance in modern cosmology. We have observed that the deceleration parameter q displays a signature-flipping point where shifting occurs from a decelerating regime to an accelerating regime, signifying cosmic expansion. It is observed that our model is in good agreement with the current scenario of accelerated expansion of the universe.
Keywords: *Domain wall; $f(Q,T)$ gravity; Axially symmetric space-time; Deceleration parameter*
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1. INTRODUCTION

Einstein's general theory of relativity (GTR) is a landmark achievement in modern physics. GTR successfully describes gravitational phenomena, solar-system dynamics and the evolution of the universe through its field equation and cosmological models. Nevertheless, the large-scale structure of the cosmos is best represented by the field equations, implying that GTR does not fully accommodate certain aspects of contemporary cosmology. For instance, it does not incorporate Mach's principle, it does not avoid singularity problems and it fails to explain the current accelerated expansion. Observational and theoretical evidence, especially from type Ia Supernovae data [1-3] suggests that the universe is not only expanding but also accelerating. According to observational evidence, especially from the Wilkinson Microwave Anisotropy Probe (WAMP) [4], energy composition of universe is made up of around 4% ordinary baryonic matter, 23% dark matter and 73% dark energy. To address these findings, two main approaches have emerged to investigate the accelerated universe: 1) developing alternative theories of gravity 2) modifying Einstein's theory of gravitation. Consequently, several modified gravity theories have been proposed by altering the Hilbert-Einstein action, such as $f(G)$ gravity [5], $f(R)$ gravity [6], $f(R,T)$ gravity [7], $f(T)$ gravity [8], $f(G,T)$ gravity [9], $f(R,T,R_{\mu\nu}T^{\mu\nu})$ gravity [10], $f(Q)$ gravity [11] and the recently proposed $f(Q,T)$ gravity [12-15].

Recently Xu et al. [12] proposed $f(Q,T)$ theory of gravity, an extension of symmetric teleparallel gravity where the Lagrangian is an arbitrary function of the non-metricity Q and the trace of energy momentum tensor T. This theory advances general relativity by introducing a coupling between Q and T. The field equations of $f(Q,T)$ can be determined by varying the gravitational action with respect to both the metric and connection. The importance of $f(Q,T)$ gravity is its ability to describe the accelerated expansion of the universe without requiring a cosmological constant, offering a unified framework for investing early-time inflation and late-time cosmic acceleration. It is possible to construct cosmologically viable models in $f(Q,T)$ theory which are consistent with general relativity. Narzary and Dewri [16] have investigated Bianchi type-VI spacetime within $f(Q,T)$ gravity in presence of bulk viscous fluid. They also examined bouncing scenario in $f(Q,T)$ gravity having Bianchi type-VI spacetime [17]. Kaczmarek et al. [18] have investigated an alternative dynamically similar scalar-tensor presentation for the $f(Q,T)$ gravity and discussed its kinetic behaviour for the FLRW cosmology. Venkatesha et al. [19] have introduced wormhole solutions including conformal symmetries and Gaussian noncommutativity within $f(Q,T)$ gravity. Gul et al. [20] studied the bouncing scenarios in a flat FRW spacetime in presence of perfect fluid matter distribution in $f(Q,T)$ gravity. Tayde et al. [21] have investigated wormhole solutions accompanied by dark matter galactic halo profiles in the context of $f(Q,T)$ gravity. Khurana et al. [22] have discussed analysis of FLRW model in $f(Q,T)$ theory produced by the cubic parametrization of the deceleration parameter. Shekh et al. [23] have discussed the dynamics of spatially flat FLRW metric in specific models of $f(Q,T)$ gravity using parametrization of the deceleration parameter. They also studied $f(Q,T)$ model with an emergent scale factor [24]. Kale et al. [25] have studied the observational constraints of two different $f(Q,T)$ models in FLRW framework using specific Hubble parameter in redshift form. Pati et al. [26] have investigated the behaviour of cosmological parameters in an isotropic and homogeneous spacetime within the framework of $f(Q,T)$ gravity. Narawade et al. [27] have investigated

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dynamical analysis and observational constraints of $f(Q,T)$ model. Xu et al. [28] studied Weyl type $f(Q,T)$ model and compared it with ΛCDM model.

During the early stages of the evolution of the universe, it is generally assumed that during cosmological phase transition, the symmetry of universe is broken spontaneously and topological stable defects such as cosmic strings and domain walls could form [29]. Domain wall separate regions with distinct vacuum states and possess large surface energy densities. Domain walls are stable due to their topological nature, originating from the configuration of vacuum manifolds during symmetry breaking [30]. Domain walls have garnered considerable interest in cosmology, especially for their involvement in galaxy formation scenario. Zel'dovich et al. [31] investigated domain interfaces, uniformity and the expanding universe. They found that domain walls must vanish early in the universe's evolution. This disappearance enables the transformation of energy density into massive quanta or equilibrium radiation, thereby achieving isotropy and homogeneity. As domain wall naturally breaks isotropy, therefore to study them in anisotropic background, models provide convincing presentation of early universe dynamics. In recent years, lots of work has been done by many researchers on domain walls. Hatkar et al. [32] have studied topological defects in LRS Bianchi type-I space time in $f(T)$ gravity. Junaid et al. [33] have explored the aspects of domain wall in Bianchi type-III universe in $f(R,T)$ theory. Hatkar et al. [34-36] explored various cosmological models with domain wall including FRW, Bianchi type-VI$_0$ and Bianchi type-I in the context of $f(Q)$, $f(R,T)$ and $f(G)$ theories of gravity. Patil et al. [37] have explored the solution of FRW space-time with bulk viscous domain wall in $f(R,T)$ gravity.

Axially symmetric spacetime plays a crucial role in the large-scale study of the universe particularly when anisotropies and inhomogeneities are not ignored [38]. Kilinc [38] demonstrated axially symmetric cosmological models have significantly contributed to understanding essential features of the universe such as galaxy formation during its early evolutionary stages. Axially symmetric cosmological models both in general relativity and in the alternative theories of gravitation have been extensively studied by Mete et al. [39], Reddy and Naidu [40-41], Adhav et al. [42], Reddy and Rao [43]. Nimkar and Wath [44] investigated an axially symmetric cosmological model with perfect fluid in Lyra geometry. Sahoo et al. [45] explored axially symmetric cosmological model in the framework of $f(R,T)$ gravity.

In this paper, we propose to investigate the axially symmetric space-time given by Bhattacharya and Karade [46] in the presence of domain wall within the framework of $f(Q,T)$ gravity. The paper is structured as follows: Section 1 contains a concise introduction and the motivation behind the current work. $f(Q,T)$ Theory and field equations is given in Section 2. In Section 3, we have derived the metric and field equations. In Section 4, we derived the solution of field equations using the linearly varying deceleration parameter and discussed the physical parameters graphically. Section 5 deals with graphical discussion of Hubble datasets. Conclusion is presented in Section 6.

2. $f(Q,T)$ THEORY AND FIELD EQUATIONS

The field equations of modified $f(Q,T)$ gravity are derived from Hilbert Einstein variational action principle

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

where $f(Q,T)$ is a function of the non-metricity scalar Q and the trace of the matter-energy-momentum tensor T , also L_m is Lagrangian of the matter and $g = \det(g_{\mu\nu})$. The non-metricity scalar Q is defined as

$$Q = -g^{\mu\nu}\left(L^{\alpha}{}_{\beta\mu}L^{\beta}{}_{\nu\alpha} - L^{\alpha}{}_{\beta\alpha}L^{\beta}{}_{\mu\nu}\right) \tag{2}$$

where $L^{\alpha}{}_{\beta\gamma}$ represents the disformation tensor which is given by,

$$L^{\alpha}{}_{\beta\gamma} = -\frac{1}{2} g^{\alpha\delta}\left(\nabla_{\gamma} g_{\beta\delta} + \nabla_{\beta} g_{\delta\gamma} - \nabla_{\delta} g_{\beta\gamma}\right) \tag{3}$$

The non-metricity tensor is defined as

$$Q_{\gamma\mu\nu} = \nabla_{\gamma} g_{\mu\nu} \tag{4}$$

The trace of the non-metricity tensor is derived as follows

$$Q_{\alpha} = g^{\mu\nu} Q_{\alpha\mu\nu}\, , \tilde{Q}_{\alpha} = g^{\mu\nu} Q_{\mu\alpha\nu} \tag{5}$$

The superpotential or the non-metricity conjugate of the model is given by

$$P^{\alpha}{}_{\mu\nu} = -\frac{1}{2} L^{\alpha}{}_{\mu\nu} + \frac{1}{4}\left(Q^{\alpha} - \tilde{Q}^{\alpha}\right) g_{\mu\nu} - \frac{1}{4} \delta^{\alpha}{}_{(\mu} Q_{\nu)} \tag{6}$$

The energy-momentum tensor is defined as

$$T_{\mu\nu} = -\frac{2}{\sqrt{-g}}\frac{\delta(\sqrt{-g}L_m)}{\delta g^{\mu\nu}} \quad \text{and} \quad \theta_{\mu\nu} = g^{\alpha\beta}\frac{\delta T_{\alpha\beta}}{\delta g^{\mu\nu}} \tag{7}$$

The field equation of $f(Q,T)$ gravity is obtained by varying the action (1) with respect to the metric tensor $g_{\mu\nu}$ as

$$-\frac{2}{\sqrt{-g}}\nabla_\alpha\left(f_Q\sqrt{-g}P^\alpha{}_{\mu\nu}\right) - \frac{1}{2}f g_{\mu\nu} + f_T\left(T_{\mu\nu} + \theta_{\mu\nu}\right) - f_Q\left(P_{\mu\alpha\beta}Q_\nu{}^{\alpha\beta} - 2Q^{\alpha\beta}{}_\mu P_{\alpha\beta\nu}\right) = 8\pi T_{\mu\nu} \tag{8}$$

where $f_Q = \frac{\partial f}{\partial Q}$, $f_T = \frac{\partial f}{\partial T}$ and the non-metricity tensors $Q_\nu{}^{\alpha\beta} = -\nabla_\nu g^{\alpha\beta}$, $Q^{\alpha\beta}{}_\mu = g^{\alpha\gamma}g^{\beta\rho}\nabla_\gamma g_{\rho\mu}$

3. THE METRIC AND FIELD EQUATIONS

We have considered the axially symmetric space-time given by Bhattacharya and Karade [46] in the form

$$ds^2 = dt^2 - A^2[d\chi^2 + h^2(\chi)d\phi^2] - B^2dz^2 \tag{9}$$

where the metric potentials A , B are functions of cosmic time t and h is a function of coordinate χ alone.
The energy momentum tensor of domain wall [33] is

$$T_{ij} = \rho\left(g_{ij} + \omega_i\omega_j\right) + p\omega_i\omega_j \tag{10}$$

where ρ is the energy density of the wall, p is the pressure in the direction normal to the plane of the wall and ω_i is a unit space like vector in the same direction with $\omega^i\omega_j = -1$. Here pressure is taken in the direction of x-axis. The quantities ρ and p depends on t only. Additionally, $\rho = \rho_b + \sigma_d$ and $p = p_b - \sigma_d$ where p_b and ρ_b denote the pressure and energy density of barotropic fluid, σ_d stands for the tension of domain wall.
Then, we have

$$T_0^0 = T_2^2 = T_3^3 = \rho \ , \ T_1^1 = -p \ , \ T = 3\rho - p \tag{11}$$

θ_j^i is derived as

$$\theta_j^i = \delta_j^i p - 2T_j^i = \text{diag}\,(p - 2\rho, 3p, p - 2\rho, p - 2\rho) \tag{12}$$

For given cosmological model, the non-metricity scalar Q is found to be

$$Q = -2\left(\frac{\dot{A}^2}{A^2} + 2\frac{\dot{A}\dot{B}}{AB}\right) \tag{13}$$

The field equation (8) for the line element (9) with energy momentum tensor (11), also using equation (12) and (13) can be written as

$$\frac{1}{2}f + 2F\left(\frac{\dot{A}^2}{A^2} + 2\frac{\dot{A}\dot{B}}{AB}\right) = 8\pi\left(1 + \tilde{G}\right)\rho - 8\pi\tilde{G}p \tag{14}$$

$$\frac{1}{2}f + F\left(\frac{\ddot{A}}{A} + \frac{\ddot{B}}{B} + \frac{\dot{A}^2}{A^2} + 3\frac{\dot{A}\dot{B}}{AB}\right) = 8\pi(1 + 2\tilde{G})p \tag{15}$$

$$\frac{1}{2}f + F\left(\frac{\ddot{A}}{A} + \frac{\ddot{B}}{B} + \frac{\dot{A}^2}{A^2} + 3\frac{\dot{A}\dot{B}}{AB}\right) = 8\pi\tilde{G}p - 8\pi(1 + \tilde{G})\rho \tag{16}$$

$$\frac{1}{2}f + 2F\left(\frac{\ddot{A}}{A} + \frac{\dot{A}^2}{A^2} + \frac{\dot{A}\dot{B}}{AB}\right) = 8\pi\tilde{G}p - 8\pi(1 + \tilde{G})\rho \tag{17}$$

where $F = f_Q$, $f_T = 8\pi\tilde{G}$ and an overhead dot refers to derivative with respect to time t.
For the given cosmological model, the physical parameters are defined as follows. The average scale factor a and the spatial volume V are expressed as

$$a = (A^2B)^{\frac{1}{3}} \tag{18}$$

$$V = a^3 = A^2B \tag{19}$$

The generalized mean Hubble's parameter H is expressed as

$$H = \frac{1}{3}(H_1 + H_2 + H_3) \tag{20}$$

where $H_1 = H_2 = \frac{\dot{A}}{A}$, $H_3 = \frac{\dot{B}}{B}$ are the directional Hubble parameters in the direction of χ, ϕ, z respectively.
We define the expansion scalar θ and the shear scalar σ^2 as

$$\theta = 2\frac{\dot{A}}{A} + \frac{\dot{B}}{B} \tag{21}$$

$$\sigma^2 = \frac{1}{2}\left[\sum_{i=1}^{3} H_i^{\,2} - \frac{\theta^2}{3}\right] = \frac{1}{3}\left(\frac{\dot{A}}{A} - \frac{\dot{B}}{B}\right)^2 \tag{22}$$

The mean anisotropy parameter Δ is given by

$$\Delta = \frac{1}{3}\sum_{i=1}^{3}\left(\frac{H_i - H}{H}\right)^2 \tag{23}$$

4. SOLUTIONS OF THE FIELD EQUATIONS AND DISCUSSION OF THE PHYSICAL PARAMETERS

There are various forms of the function $f(Q,T)$ which is commonly used in Literature [12]. Here we shall focus on the linear and additive form of $f(Q,T)$ function [28] as $f(Q,T) = \mu Q + \nu T$. Here μ and ν are non-zero arbitrary constants.
Here $F = f_Q = \mu,\ f_T = \nu = 8\pi\tilde{G}$, $\tilde{G} = \frac{\nu}{8\pi}$.

As the system of equations (14) - (17) being highly non-linear, we assume a relation between the metric coefficients by employing the physical assumption that the expansion scalar θ is proportional to shear scalar σ . This assumption was employed by Collins et al. [47] and has recently been used by Junaid et al. [33] and Hatkar et al. [36] to obtain solution of field equations. From this, we derive the following relation.

$$A = B^n \ \ , \ n > 0 \tag{24}$$

where n is an arbitrary constant such that for $n \neq 1$, the space time is anisotropic nature.

Berman [48] and Berman and Gomide [49] suggested a law of variation of the Hubble parameter in FLRW framework which gives a constant deceleration parameter ($q = m - 1, m \geq 0$ is a constant). After the discovery of the universe's accelerated expansion, researchers have investigated cosmological models that employ Berman's law in the context of dark energy. In Berman's law, deceleration parameter can take values $q \geq -1$ and $-1 \leq q < 0$, corresponding to accelerating expansion. The time-varying deceleration parameter plays a crucial role in the universe's evolution, as it captures the transition in expansion dynamics. We solve the system of highly non-linear equations (14) - (17) with the help of the linearly varying deceleration parameter proposed by Akarsu and Dereli [50] in the form

$$q = -\frac{a\ddot{a}}{\dot{a}^2} = -kt + m - 1 \tag{25}$$

where $k \geq 0$ and $m \geq 0$ are constants. The above deceleration parameter give rise to three different cases as follows:

- $q = -1$ for $k = 0, m = 0$
- $q = m - 1$ for $k = 0, m > 0$
- $q = -kt + m - 1$ for $k > 0, m \geq 0$

For $q > 0$ the universe shows decelerating expansion, for $q = 0$ it shows constant rate of expansion, if $-1 < q < 0$ it represents accelerating expansion (referred as power law expansion), de Sitter expansion for $q = -1$ (called as exponential expansion) & superexponential for $q < -1$. For $k = 0$ i.e. first two cases correspond to Berman's law of constant deceleration parameter. Therefore, only the last case i.e. for $k > 0$ the linearly varying deceleration parameter ($q = -kt + m - 1$) fits well with modern observational data, indicating a time-dependent transition in the universe's expansion. Here we consider case– I: $k = 0$ and $m > 0$ and case– II: $k \neq 0$ and $m \geq 0$ to obtain solution of the field equations.

Case-I: Let $k = 0$ and $m > 0$

After solving equation (25), we obtain mean scale factor as

$$a = (\alpha t + \beta)^{\frac{1}{m}} \tag{26}$$

where α and β are constant of integration.

With the help of (18), (24) and (26), the metric potentials A and B are obtained as

$$A = (\alpha t + \beta)^{\frac{3n}{m(2n+1)}} \tag{27}$$

$$B = (\alpha t + \beta)^{\frac{3}{m(2n+1)}} \tag{28}$$

From equation (27) and (28), it is seen that initially A and B are constants for $t = 0$. When $t \to -\frac{\beta}{\alpha}$, they tend to zero and become infinite for increasing t.
Using equations (27), (28) in (9), we obtain the cosmological model given by Bhattacharya and Karade in $f(Q,T)$ gravity in presence of domain wall in the form:

$$ds^2 = dt^2 - (\alpha t + \beta)^{\frac{6n}{m(2n+1)}} [d\chi^2 + h^2(\chi)d\phi^2] - (\alpha t + \beta)^{\frac{6}{m(2n+1)}} dz^2 \tag{29}$$

From equations (20) – (22) with the use of (27) and (28), the physical parameters such as Hubble parameter H, the expansion scalar θ and the shear scalar σ^2 are obtained as

$$H = \frac{\alpha}{m(\alpha t+\beta)} \tag{30}$$

$$\theta = \frac{3\alpha}{m(\alpha t+\beta)} \tag{31}$$

$$\sigma^2 = \frac{3\alpha^2(n-1)^2}{m^2(2n+1)^2(\alpha t+\beta)^2} \tag{32}$$

We can observe that at the initial time $t = -\frac{\beta}{\alpha}$, all three quantities the Hubble parameter H, the expansion scalar θ and the shear scalar σ^2 are infinite and subsequently decay to zero as $t \to \infty$. This behaviour signifies a very rapid expansion of the universe. The non-zero ratio $\frac{\sigma}{\theta}$ indicates an anisotropic universe, representing the early phase of cosmic evolution.
The spatial volume is

$$V = (\alpha t + \beta)^{\frac{3}{m}} \tag{33}$$

Spatial volume and average scale factor are constant at $t = 0$, indicating that the universe starts evolving with finite volume at initial time and expanded over time.
The mean anisotropy parameter is found to be

$$\Delta = \frac{2(n-1)^2}{(2n+1)^2} \quad , n \neq -\frac{1}{2} \tag{34}$$

The parameter n determines the anisotropic nature of the model such that for $n = 1$ the model becomes isotropic, whereas for $n \neq 1$ the anisotropic character is preserved.
The pressure p is found to be

$$p = \frac{3\mu\alpha^2\xi}{m^2(2n+1)^2(\alpha t+\beta)^2} \tag{35}$$

where $\xi = \frac{\left(8\pi-\frac{\nu}{2}\right)(n+1)(3-2mn-m)+3n[(8\pi+\nu)n+3\nu]}{64\pi^2+16\pi\nu-2\nu^2}$

From Fig. 1, we observed that pressure p is decreasing function of time t .
For this model, energy density ρ is obtained as

$$\rho = \frac{3\mu\alpha^2}{m^2(2n+1)^2(\alpha t+\beta)^2\left(8\pi-\frac{\nu}{2}\right)}\left\{3(n^2+2n) + \frac{\nu\xi}{2}\right\} \tag{36}$$

The relation between pressure and energy density of barotropic fluid is given as

$$p_b = (\gamma - 1)\rho_b \quad \text{where } 1 \leq \gamma \leq 2 \tag{37}$$

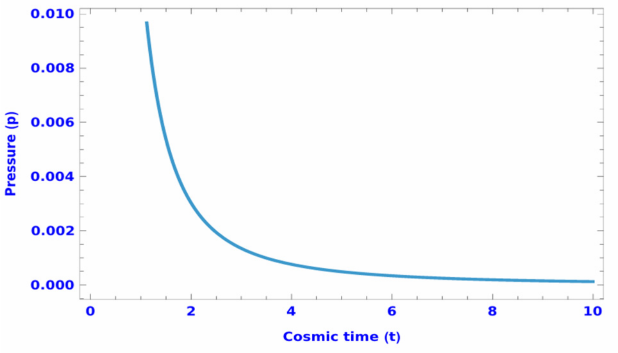

Figure 1. Plot of Pressure vs cosmic time *t* with α = 64.15, $\mu = \nu = \beta = n$ = 0.1, *m* = 1.12

The expression for tension of domain wall is found to be

$$\sigma_d = \frac{3\mu\alpha^2}{\gamma m^2(2n+1)^2(\alpha t+\beta)^2}\left\{\frac{\gamma-1}{\left(8\pi-\frac{\nu}{2}\right)}\left[3(n^2+2n)+\frac{\nu\xi}{2}\right]-\xi\right\} \tag{38}$$

Figure 2 shows the graphical behaviour of energy density ρ and tension density ρ_d versus cosmic time t. Energy density ρ is a decreasing function of time t, whereas tension of the domain wall is an increasing function of time t. Energy density is large as $t \to 0$ and tends to zero as $t \to \infty$. The tension of the domain wall is negative throughout the universe evolution as shown in Fig. 2. The domain wall acts like invisible matter due to its negative tension. The domain wall exists initially and thereafter vanished which is as per expectation Zel'dovich et al [31].

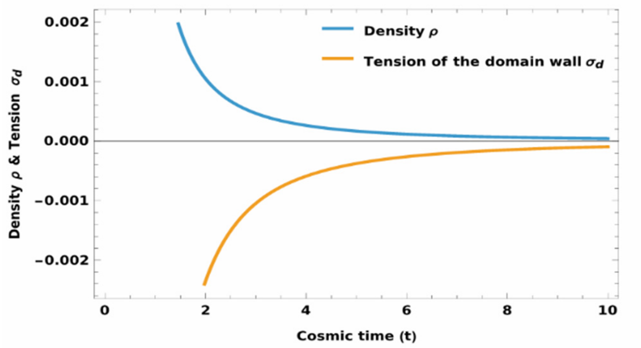

Figure 2. Plot of Density & Tension of the domain wall vs cosmic time *t* with α = 64.15, $\mu = \nu = \beta = n$ = 0.1, *m* = 1.12, γ = 1.2

Case-II: Let $k \neq 0$ and $m \geq 0$

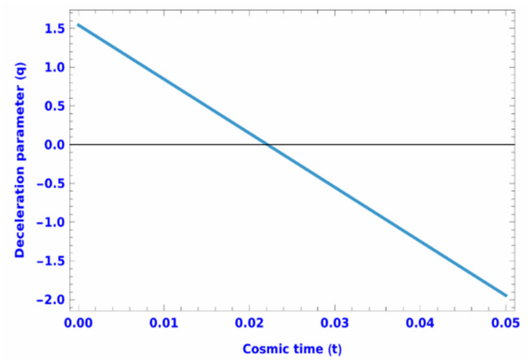

Figure 3. Plot of Deceleration parameter vs cosmic time *t* with *k* = 69.67, *m* = 2.54

Figure 3 demonstrates that the universe experiences early deceleration and present acceleration. For $q = m - 1 > 0$, the universe begins with decelerating expansion and enters to accelerating phase at $t = \frac{m-1}{k}$.
After solving equation (25), we obtain mean scale factor as

$$a = c_2 exp\left[\frac{2}{\sqrt{m^2-2c_1k}}tanh^{-1}\left(\frac{kt-m}{\sqrt{m^2-2c_1k}}\right)\right] \tag{39}$$

where c_1 and c_2 are constant of integration. For simplifying the expression, we omit the constant c_1 by choosing $c_1 = 0$.

$$a = c_2 exp\left[\frac{2}{m} tanh^{-1}\left(\frac{kt}{m} - 1\right)\right] \tag{40}$$

With the help of (18), (24) and (40), the metric potentials A and B are obtained as

$$A = c_2^{\left(\frac{3n}{2n+1}\right)} exp\left[\frac{6n}{m(2n+1)} tanh^{-1}\left(\frac{kt}{m} - 1\right)\right] \tag{41}$$

$$B = c_2^{\left(\frac{3}{2n+1}\right)} exp\left[\frac{6}{m(2n+1)} tanh^{-1}\left(\frac{kt}{m} - 1\right)\right] \tag{42}$$

From equations (41) and (42), it is noted that both metric potentials A and B are constants for $t = 0$ and diverge as $t \to \infty$. As a result, the obtained model is free from singularity.
Using equations (41), (42) in (9), we obtain the cosmological model given by Bhattacharya and Karade in $f(Q,T)$ gravity in presence of domain wall in the form:

$$ds^2 = dt^2 - \left[c_2^{\left(\frac{3n}{2n+1}\right)} exp\left[\frac{6n}{m(2n+1)} tanh^{-1}\left(\frac{kt}{m} - 1\right)\right]\right]^2 [d\chi^2 + h^2(\chi)d\phi^2] - \left[c_2^{\left(\frac{3}{2n+1}\right)} exp\left[\frac{6}{m(2n+1)} tanh^{-1}\left(\frac{kt}{m} - 1\right)\right]\right]^2 dz^2 \tag{43}$$

From equations (20) – (22) with the use of (41) and (42), the physical parameters such as Hubble parameter H, the expansion scalar θ and the shear scalar σ^2 are obtained as

$$H = \frac{-2}{(kt^2 - 2mt)} \tag{44}$$

$$\theta = \frac{-6}{(kt^2 - 2mt)} \tag{45}$$

$$\sigma^2 = \frac{12(n-1)^2}{(2n+1)^2(kt^2 - 2mt)^2} \tag{46}$$

The parameters H , θ and σ^2 tends to zero as $t \to \infty$. It is to be noted that for $n = 1$ the model is shear free and its nature will be retained for $n \neq 1$.
The spatial volume given in (19) found to be

$$V = {c_2}^3 exp\left[\frac{6}{m} tanh^{-1}\left(\frac{kt}{m} - 1\right)\right] \tag{47}$$

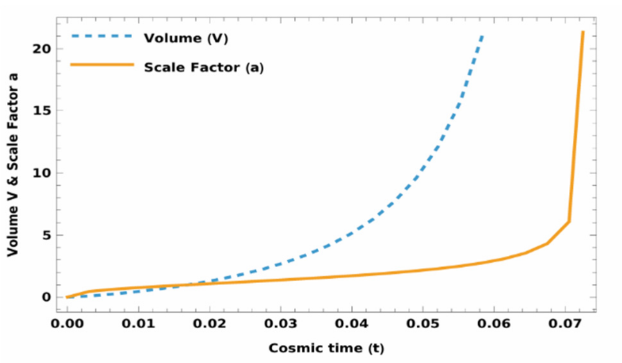

Figure 4. Plot of Volume & Scale factor vs cosmic time t with k = 69.67, m = 2.54, c_2= 1.60

Figure 4 illustrates the graphical evolution of spatial volume and average scale factor. Both these parameters are fixed at $t = 0$, signifying that the universe begins with a finite initial volume at finite time and it expands over time.
The mean anisotropy of the model is

$$\Delta = \frac{2(n-1)^2}{(2n+1)^2} \quad , n \neq -\frac{1}{2} \tag{48}$$

A parameter n decides the anisotropic behaviour of the model in the sense that, if $n = 1$,we get isotropic model and for $n \neq 1$, anisotropic nature will be retained.

The pressure p is found to be

$$p = \frac{6\mu}{(2n+1)^2(32\pi^2+8\pi\nu-\nu^2)(kt^2-2mt)^2}\left\{(n+1)(2n+1)\left(8\pi-\frac{\nu}{2}\right)(kt-m)+k_0\right\} \tag{49}$$

where $k_0 = 3(n+1)\left(8\pi-\frac{\nu}{2}\right)+3n[(8\pi+\nu)n+3\nu]$

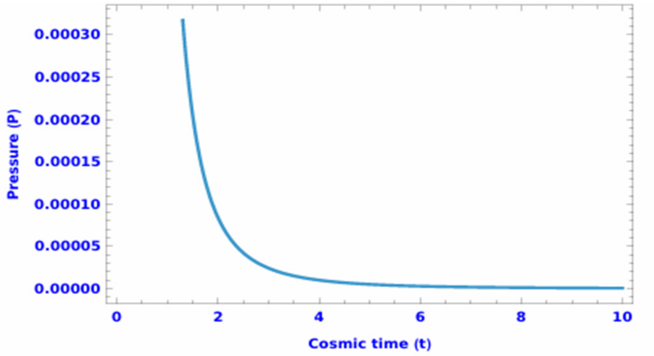

Figure 5. Plot of Pressure vs cosmic time t with k = 69.67, $\mu = \nu = n = 0.1$, m = 2.54

From Fig. 5, we observed that pressure p is decreasing function of time t .
For this model, energy density ρ is obtained as

$$\rho = \frac{3\mu}{(2n+1)^2\left(8\pi-\frac{\nu}{2}\right)(kt^2-2mt)^2}\left\{12(n^2+2n)+\frac{\nu}{(32\pi^2+8\pi\nu-\nu^2)}\left[(n+1)(2n+1)\left(8\pi-\frac{\nu}{2}\right)(kt-m)+k_0\right]\right\} \tag{50}$$

The expression for tension of domain wall is found to be

$$\sigma_d = \frac{36\mu(\gamma-1)(n^2+2n)}{\gamma(2n+1)^2\left(8\pi-\frac{\nu}{2}\right)(kt^2-2mt)^2}+\frac{3\mu\left[(n+1)(2n+1)\left(8\pi-\frac{\nu}{2}\right)(kt-m)+k_0\right]}{\gamma(2n+1)^2(32\pi^2+8\pi\nu-\nu^2)(kt^2-2mt)^2}\left\{\frac{\gamma(\gamma-1)}{\left(8\pi-\frac{\nu}{2}\right)}-2\right\} \tag{51}$$

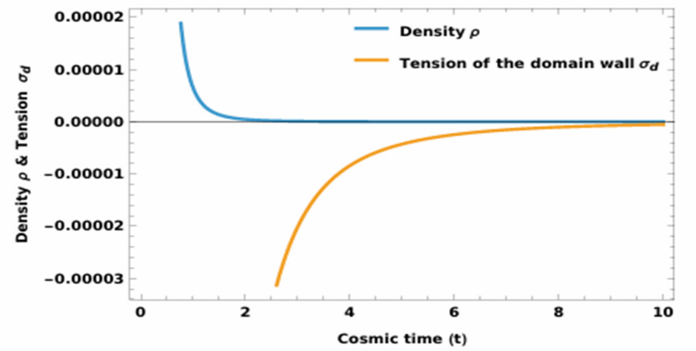

Figure 6. Plot of Density & Tension of the domain wall vs cosmic time t with k = 69.67, $\mu = \nu = n = 0.1$, m = 2.54, γ = 1.2

Figure 6 illustrates the graphical behaviour of energy density ρ and tension density ρ_d. We observed that energy density ρ is a decreasing function of time t. Density becomes zero as $t \to \infty$. The tension of the domain wall is negative throughout and it gradually increases to zero. The domain wall acts like invisible matter. This shows that the domain wall was present during the early stages of the universe, later on it disappeared.

5. HUBBLE DATASETS

The Hubble parameter is employed in observational cosmology to examine the universe's expansion. The Hubble parameter for case- I and case- II can be expressed in terms of redshift as

$$\text{For case– I :} \quad H = \frac{\alpha}{m(1+z)^{-m}} \tag{52}$$

$$\text{For case– II :} \quad H = \frac{k}{m^2}\left\{1+cosh\left(m\ln\left(\frac{1}{c_2(1+z)}\right)\right)\right\} \tag{53}$$

To estimate $H(z)$ at a given redshift, two widely used techniques are the line-of-sight baryon acoustic oscillation (BAO) method and another is the different age (DA) approach, cited in references [51-69]. In this work, a revised dataset of 57 points is used which includes 31 points from DA approach and the remaining 26 points measured using BAO and various redshift range $0.07 \leq z \leq 2.42$ [70]. Table 1 shows the 57 points of Hubble parameter values $H(z)$ having errors σ_H along with references from DA (31 points) and BAO and other (26 points) approaches. Additionally, the present Hubble constant $H_0 = 67.8$ km/s/Mpc was adopted for the analysis.

Table 1. Hubble datasets

z	$H(z)$	σ_H	Ref.	z	$H(z)$	σ_H	Ref.
0.070	69	19.6	[51]	1.750	202	40	[52]
0.90	69	12	[52]	1.965	186.5	50.4	[57]
0.120	68.6	26.2	[51]	0.24	79.69	2.99	[58]
0.170	83	8	[52]	0.30	81.7	6.22	[59]
0.1791	75	4	[53]	0.31	78.18	4.74	[60]
0.1993	75	5	[53]	0.34	83.8	3.66	[58]
0.200	72.9	29.6	[54]	0.35	82.7	9.1	[61]
0.270	77	14	[52]	0.36	79.94	3.38	[60]
0.280	88.8	36.6	[54]	0.38	81.5	1.9	[62]
0.3519	83	14	[53]	0.40	82.04	2.03	[60]
0.3802	83	13.5	[55]	0.43	86.45	3.97	[58]
0.400	95	17	[52]	0.44	82.6	7.8	[63]
0.4004	77	10.2	[55]	0.44	84.84	1.83	[60]
0.4247	87.1	11.2	[55]	0.48	87.79	2.03	[60]
0.4497	92.8	12.9	[55]	0.51	90.4	1.9	[62]
0.470	89	34	[56]	0.52	94.35	2.64	[60]
0.4783	80.9	9	[55]	0.56	93.34	2.3	[60]
0.480	97	62	[51]	0.57	87.6	7.8	[64]
0.593	104	13	[53]	0.57	96.8	3.4	[65]
0.6797	92	8	[53]	0.59	98.48	3.18	[60]
0.7812	105	12	[53]	0.60	87.9	6.1	[63]
0.8754	125	17	[53]	0.61	97.3	2.1	[62]
0.880	90	40	[51]	0.64	98.82	2.98	[60]
0.900	117	23	[52]	0.73	97.3	7.0	[63]
1.037	154	20	[53]	2.30	224	8.6	[66]
1.300	168	17	[52]	2.33	224	8	[67]
1.363	160	33.6	[57]	2.34	222	8.5	[68]
1.430	177	18	[52]	2.36	226	9.3	[69]
1.530	140	14	[52]				

Figures 7 and 8 shows the best fit plot of Hubble parameter $H(z)$ as a function of redshift z for case-I , case-II respectively. By comparing the Hubble parameter graph to the Hubble data set , we observed that ΛCDM model fits the best-fit model very closely, matching the data ponits (see Table 1) using the parameters H_0, α, k, m, c_2 . Despite the presence of error bars, the best-fit curve stays within the data's uncertainty range, confirming the reliability of the fit.

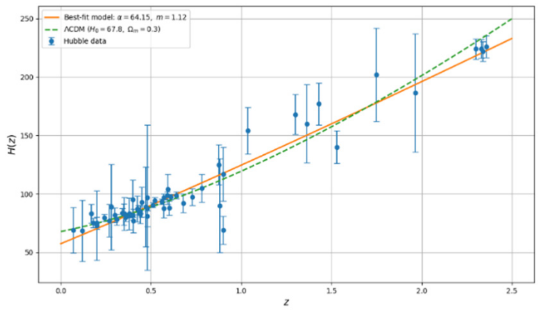

Figure 7. The best fit plot of Hubble parameter *H(z)* vs redshift for case-I

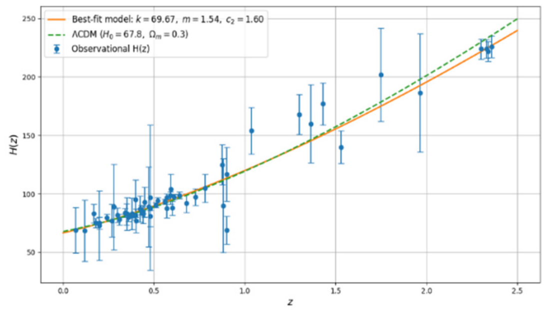

Figure 8. The best fit plot of Hubble parameter *H(z)* vs redshift for case-II

6. CONCLUSION

In this paper, we have investigated the cosmological model given by Bhattacharya and Karade in $f(Q,T)$ gravity in presence of domain wall. We have derived the exact solution of the field equations by considering the linearly varying deceleration parameter in two cases. We have determined some physical parameters to analyze the behaviour of universe. The behaviour of the physical parameters i.e. $\sigma, V, a, \Delta, p, \rho, \sigma_d$ are same in both the cases. The parameters spatial volume and average scale factor are constant at $t = 0$, indicating that the universe starts evolving with finite volume at initial time and expanded over time. The ratio $\frac{\sigma}{\theta} \neq 0$ as $t \to \infty$ and hence the model does not approach isotropy. The mean anisotropy parameter is uniform throughout expansion of the universe. The deceleration parameter decides whether the universe expansion is accelerating or decelerating. In case–II, Fig. 3 shows that the universe has undergone multiple phases, beginning with an initial deceleration phase and finishing with the present acceleration era. As the cosmic time approaches infinity, both the Hubble parameter and the expansion scalar tend toward zero. This implies the universe's expansion is becoming steady. Pressure and energy density decreases as cosmic time increases. The tension of the domain wall is negative throughout and it gradually increases to zero. Finally, the close match between the plotted curve and the Hubble data confirms the model's accuracy in describing the relationship between redshift and the Hubble parameter, providing further evidence for an expanding universe.

Our findings have shed light on the universe's cosmological evolution, specifically its shift from a decelerating to an accelerating expansion. Our analysis reveals how the cosmological parameters changes over time, highlighting the significance of modified gravity theories in explaining the current rapid expansion. Our results not only confirm the applicability of $f(Q,T)$ gravity in modern cosmological studies but also create opportunities for more in-depth examinations of domain wall and its impact on the universe's evolution.

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АКСІАЛЬНО-СИМЕТРИЧНА КОСМОЛОГІЧНА МОДЕЛЬ В ГРАВІТАЦІЇ *f*(*Q*,*T*)

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Ця стаття присвячена вивченню динамічних аспектів космологічної моделі доменної стінки в осьово-симетричному просторі-часі в гравітації f(Q,T). У цій теорії гравітації дія містить довільну функцію f(Q,T), де Q та T відповідно позначають неметричність та слід тензора енергії-імпульсу. У цій роботі враховується лінійна та адитивна форма гравітації f(Q,T), f(Q,T)=μQ+νT, де μ та ν – ненульові довільні константи. Детерміновану модель Всесвіту отримано з використанням лінійно змінного параметра уповільнення q=-kt+m-1, який є лінійним у часі з негативним нахилом. Ми оцінили всі динамічні та геометричні параметри моделей та дослідили їх фізичне значення в сучасній космології. Ми спостерігали, що параметр уповільнення q демонструє характерну точку перевороту, де відбувається перехід від режиму уповільнення до режиму прискорення, що свідчить про космічне розширення. Помічено, що наша модель добре узгоджується з сучасним сценарієм прискореного розширення Всесвіту.

Ключові слова: *доменна стінка; гравітація f(Q,T); аксіально симетричний простір-час; параметр уповільнення*