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THE BEHAVIOUR OF MAGNETIZED STRANGE QUARK MATTER ON BIANCHI TYPE-I UNIVERSE IN THE FRAMEWORK OF $f(R,T)$ THEORY OF GRAVITY

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Abstract: In this study, we examine a Bianchi type-I cosmological model filled with Magnetized strange quark matter (MSQM) within the framework of $f(R,T)$ gravity. To obtain solutions of the modified field equations, we employ dynamical cosmological parameters by using an equation of state (EoS) for strange quark matter in the Bianchi type-I universe. The corresponding magnetic field is also derived. Furthermore, various physical and geometrical characteristics of the model are calculate and discussed.

Keywords: Bianchi Type-I space time, $f(R,T)$ theory of gravity and Magnetized strange quark matter (MSQM).

1. Introduction:

Recent observations of the Universe's accelerated expansion and the presence of dark matter have created significant challenges for existing gravitational theories. One approach to addressing these issues is to consider that Einstein's general relativity may not fully describe gravity on very large scales, and that a more general framework is required. In this context, modified gravity models particularly those where the standard Einstein–Hilbert action is replaced by a function of the Ricci scalar, commonly referred to as $f(R)gravity$ have been widely explored. These models can successfully account for the late-time acceleration of the Universe. Although many such models initially struggled to satisfy constraints from Solar System tests, subsequent work has shown that viable versions can be constructed that remain consistent with local gravitational observations. Some of these models also attempt to unify early-time inflation with late-time cosmic acceleration and even provide alternative explanations for galactic dynamics without invoking dark matter.

Further developments extend $f(R)$ gravity by introducing a direct coupling between geometry and matter, where the Ricci scalar interacts explicitly with the matter Lagrangian. This non-minimal coupling leads to deviations from geodesic motion, producing an additional force acting on massive particles. Such frameworks have been linked to alternative theories like Modified Newtonian Dynamics (MOND) and have been used to investigate various astrophysical and cosmological phenomena. More general formulations allow arbitrary couplings in both the geometric and matter sectors, and have been studied using different approaches, including the Palatini formalism.

An even broader generalization considers gravitational actions that depend on both the Ricci scalar and the matter Lagrangian, often denoted as $f(R,L_{m)}$ gravity. One of the hot topic issue between cosmologists and astrophysicists is the accelerated expansion problem of the universe. The common view suggests to explain the expansion of the universe is dark energy and modified alternative theories. Major alternative theories are $f\ (R)$ theory **[1]**, $f\ (G)$ theory **[2]**, $f(R,T\ )$ theory Harko et al. **[3]** suggests $f\ (R,T\ )$ theory to explain accelerated expansion of the universe. They propose three models for the solution of this theory i.e. $f(R,T\ )\ =\ R\ +\ 2f\ (T\ )$, $f(R,T\ ) =\ f_1(R) +\ f_2(T\ )$ and $f(R,T\ )\ = f_1(R)\ + f_2(R)f_3(R)$ respectively. This theory represents interaction between curvature and matter. After Harko et al., this theory has been studied by several cosmologists and astrophysicists with various matter distributions and geometries to explain accelerated expansion of the universe **[4-16]**. Although the origin of the magnetic field is still unknown, magnetic fields have significant role in the early universe **[17].** Generally, quark matter (QM) is modelling with an equation of state (EoS) based on the bag model of QM. The relation between the quark pressure and density is defined by strange quark matter equation of state as follows: $p = \frac{\rho - 4B_c}{3}$, here B_c is bag constant **[18] , [19]**. Also, this constant is given between diverse values Bag constant B_c has been described the range of 60−80 $MeV/(fm)^3$ by Chakraborty et al**. [20-21]**.

In this context, Aygun et al. have researched SQM solutions for Marder type universe model in $f(R,T)$ theory **[22]**. Also, Aktas¸ and Aygun have investigated MSQM distribution for FRW universe model in $f(R,T)$ gravity **[23]**. However, Agrawal and Pawal have studied quark and SQM for plane symmetric cosmological model in $f(R,T)$ gravity **[24]**. Sahoo et al. **[25]** have researched MSQM dynamics in $f(R,T)$ gravity. C¸aglar and Aygun **[26]** have investigated Bianchi type I universe model with quark matter distributions in $f(R,T)$ gravity theory.

In the last few years, evidence has mounted indicating that some constants, which were earlier treated as true constants, are no longer constant in cosmology. The examples are Einstein's cosmological constant (Λ), Newtonian's gravitational constant(G), the fine structure constant, etc. Different phenomenological models have been suggested to explain the evolutions of different constants. Whatever physical process is responsible for the evolution of one parameter, should also be responsible for the evolution of others, implying that the different parameters are coupled together somehow. It should, therefore, be the evolution of the universe itself which should explain the dynamics of all the parameters. So, cosmological models with variable Newtonian gravitational constant G and cosmological constant Λ are of great interest for present researchers. Now we describe briefly the motivation for considering the different parameters and their variations. The one which comes first in the list is undoubtedly the Einstein's cosmological parameter Λ, whose existence is favored by the recent supernovae (SNe) Ia observations **[27-31]** and which is also consistent with the recent anisotropy measurements of the cosmic microwave background (CMB) made by the Wilkinson Microwave Anisotropy Probe (WMAP) experiment **[32]**. However, there is a fundamental problem related with the existence of Λ, which has been extensively discussed in the literature. Its value expected from the quantum field theory-calculations is about 120 orders of magnitude higher than that estimated from the observations. A phenomenological solution to this problem is suggested by considering Λ as a function of time t so that it was large in the early universe and got reduced with the expansion of the universe **[33-38]**. A number of authors studied cosmological model with a variable cosmological constant. Bertolami **[39]** was the first to consider cosmological models with a variable cosmological constant as the form of $\Lambda \propto t^{-2}$. Chen and Wu **[40]** studied Friedmann-Robertson-Walker (FRW) models with variable cosmological constant as the form $\Lambda \propto R^{-2}$, where R is the scale factor of the universe. The authors of **[41-44]** investigated cosmological models with a variable cosmological constant by considering a more general Λ term.

In recent years, growing observational and theoretical evidence suggests that certain quantities once regarded as fundamental constants in cosmology may, in fact, vary over time. Notable examples include Einstein's cosmological constant(Λ), Newton's gravitational constant(G), and the fine-structure constant. To account for such potential variations, several phenomenological models have been proposed. If a single underlying physical mechanism drives the evolution of one of these parameters, it is reasonable to expect that it also influences others, implying an intrinsic connection among them. Consequently, the overall evolution of the universe itself should provide a unified explanation for the behavior of these quantities. This perspective has led to significant interest in cosmological models that incorporate time-dependent forms of both G and Λ.

Motivated by the preceding study, we investigate the behavior of a Bianchi Type-I cosmological model incorporating Magnetized strange quark matter within the framework of $f(R,T)$ gravity. Additionally, the physical and dynamical properties of the Universe are examined. The paper is organized as follows: **Section 2**, discusses the $f(R,T)$ gravity theory and their solutions. In **Section 3**, we have studied the metric Bianchi type-I and field equations for $f(R,T)$ gravity. **Section 4,** is devoted to the solutions of field equations. In **Section5**, We have discussed the some physical and dynamical parameters. In **Section6**, Result and Discussion. Finally, in **Section 7**, we have concluded our work.

2. Modified $f(R,T)$ Gravitation Theory and Their Solutions

In 2011, Harko et al. **[3]** have suggested new alternative gravitation theory which is defined by Aygun et al.; in $f\ (R,T)$ theory. The action of this theory is given by

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

Where $f(R,T)$ is a function of Ricci scalar R and stress of energy tensor of matter T also L_m is Lagrangian of the matter. The stress energy of the matter is

$$T_{ij} = \frac{2}{\sqrt{-g}}\frac{\delta(\sqrt{-g})}{\delta g^{ij}}L_m, \quad \theta = -2T_{ij} - pg_{ij} \tag{2}$$

The corresponding field equations of $f(R,T)$ gravity are obtained by varying the action principal with respect to g_{ij} as

$$f_R(R,T)R_{ij} - \frac{1}{2}f(R,T)g_{ij} + \left(g_{ij}\nabla^i\nabla_j - \nabla_i\nabla_j\right)f_R(R,T) = 8\pi T_{ij} - f_T(R,T)T_{ij} - f_T(R,T)\theta_{ij} \tag{3}$$

Where $f_R = \frac{\partial f(R,T)}{\partial R}$, $f_R = \frac{\partial f(R,T)}{\delta T}$ and $\theta_{ij} = g^{\alpha\beta}\frac{\partial T_{\alpha\beta}}{\partial g^{\alpha\beta}}$. Here ∇ is the covarient derivative and T_{ij} is the energy momentum tensor derived from the Lagrangian L_m. Choosing the function $f(R,T) = f(R)$ the equation reduces to find the equations of $f(R)$ gravity. The field equation $f(R,T)$ depend on the physical nature of matter field, the given three model are

$$f(R,T) = \begin{cases} R + 2f(T), \\ f_1(R) + f_2(T), \\ f_1(R) + f_2(R)f_3(T). \end{cases} \tag{4}$$

3. Field Equation and Its Solution

Bianchi type- I space-time universe model is given by

$$ds^2 = -dt^2 + A^2dx^2 + B^2dy^2 + C^2dz^2 \tag{5}$$

Where A, B and C are functions of t only

The energy momentum tensor of MSQM distribution is defined as

$$T_{ij} = (p + \rho + h^2)u_iu_j + \left(p + \frac{h^2}{2}\right)g_{ij} - h_ih_j \tag{6}$$

Where T_{ij} is the energy momentum tensor and ρ is the energy density, p is the pressure of MSQM, h^2 represents the magnetic field and u_i is the four velocity vector. We can choose magnetic flux in the direction of x due to $u_ih_i = 0$.

The equations of $f(R,T)$ gravitation theory are given by

$$G_{ij} = \left(8\pi + 2f'(T)\right)T_{ij} + [2pf'(T) + f(T) + \Lambda]g_{ij} \tag{7}$$

Here $f'(T) = \frac{df(T)}{dT}$. If we take $(T) = \mu T$, where μ is a constant and the trace of energy momentum tensor is given by $T = \rho - 3p$.

Then the modified line element (5) takes the form

$$\frac{\ddot{B}}{B}+\frac{\ddot{C}}{C}+\frac{\dot{B}\dot{C}}{BC}=(4\pi+\mu)h^2-(8\pi+3\mu)p+\mu\rho+\Lambda \quad (8)$$

$$\frac{\ddot{A}}{A}+\frac{\ddot{C}}{C}+\frac{\dot{A}\dot{C}}{AC}=-(4\pi+\mu)h^2-(8\pi+3\mu)p+\mu\rho+\Lambda \quad (9)$$

$$\frac{\ddot{A}}{A}+\frac{\ddot{B}}{B}+\frac{\dot{A}\dot{B}}{AB}=-(4\pi+\mu)h^2-(8\pi+3\mu)p+\mu\rho+\Lambda \quad (10)$$

$$\frac{\dot{A}\dot{B}}{AB}+\frac{\dot{B}\dot{C}}{BC}+\frac{\dot{A}\dot{C}}{AC}=(4\pi+\mu)h^2+(8\pi+3\mu)\rho-\mu p+\Lambda \quad (11)$$

4. Solution of the Field Equations

Here the system of equation (8) to (11) has seven unknowns $A, B, C, \rho, p, h^2, \Lambda$ so we are using two conditions

$A = B^m$ and $C = B^n$ where $m \neq 1$ and $n \neq 1$ are constant (12)

Subtracting (9) from (10) we have

$$\frac{\dot{A}\dot{B}}{AB}+\frac{\ddot{B}}{B}-\frac{\dot{A}\dot{C}}{AC}-\frac{\ddot{C}}{C}=0 \quad (13)$$

By using conditions (12) we have

$$A=(k_1+1)^{mk}(k_2t+k_3)^{mk} \quad (14)$$

$$B=(k_1+1)^{k}(k_2t+k_3)^{k} \quad (15)$$

$$C=(k_1+1)^{nk}(k_2t+k_3)^{nk} \quad (16)$$

Where k and k_1 are arbitrary constants.

From equation (14), (15) and (16), Equation (5) can be written as

$$ds^2=-dt^2+[(k_1+1)^{2mk}(k_2t+k_3)^{2mk}]dx^2+[(k_1+1)^{2k}(k_2t+k_3)^{2k}]dy^2+[(k_1+1)^{2nk}(k_2t+k_3)^{2nk}]dz^2 \quad (17)$$

5. Some Physical and Dynamical Parameters

These parameters are very useful for the discussion of the properties of the cosmological model have describe some parameters for the metric given by equation (17)

Average scale factor:

$$a(t)=(ABC)^{\frac{1}{3}}=(k_1+1)^{\frac{(m+n+1)k}{3}}(k_2t+k_3)^{\frac{(m+n+1)k}{3}} \quad (18)$$

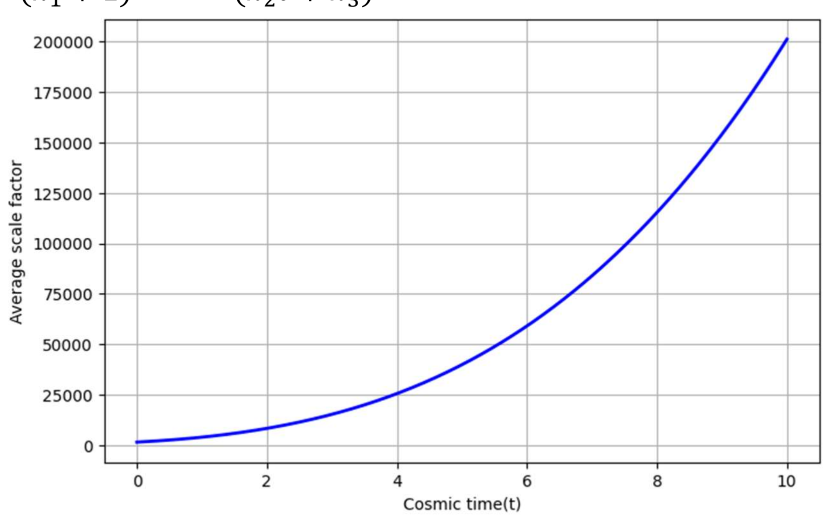

Fig1: Average Scale Factor $a(t)$ versus Cosmic time (t)

Spatial volume:

$$V=(ABC)=(k_1+1)^{(m+n+1)k}(k_2t+k_3)^{(m+n+1)k} \quad (19)$$

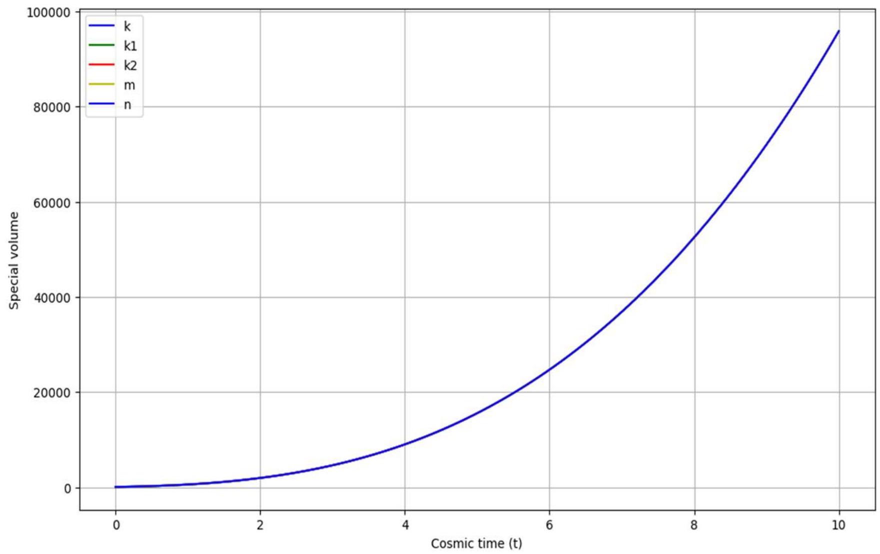

Fig2: Spatial Volume (V) versus Cosmic Time (t)

Directional Hubble Parameters:

$$H_x = \frac{\dot{A}}{A} = \frac{mkk_2(k_1+1)^{mk}(k_2t+k_3)^{mk-1}}{(k_1+1)^{mk}(k_2t+k_3)^{mk}} = \frac{mc_1}{(k_2t+k_3)} \quad (20)$$

$$H_y = \frac{\dot{B}}{B} = \frac{c_1}{(k_2t+k_3)} \quad (21)$$

$$H_z = \frac{\dot{C}}{C} = \frac{nc_1}{(k_2t+k_3)} \quad (22)$$

The average Hubble parameter is

$$H = \frac{1}{3}\left(H_x + H_y + H_z\right) = \frac{c_1(m+n+1)}{3(k_2t+k_3)} \quad (23)$$

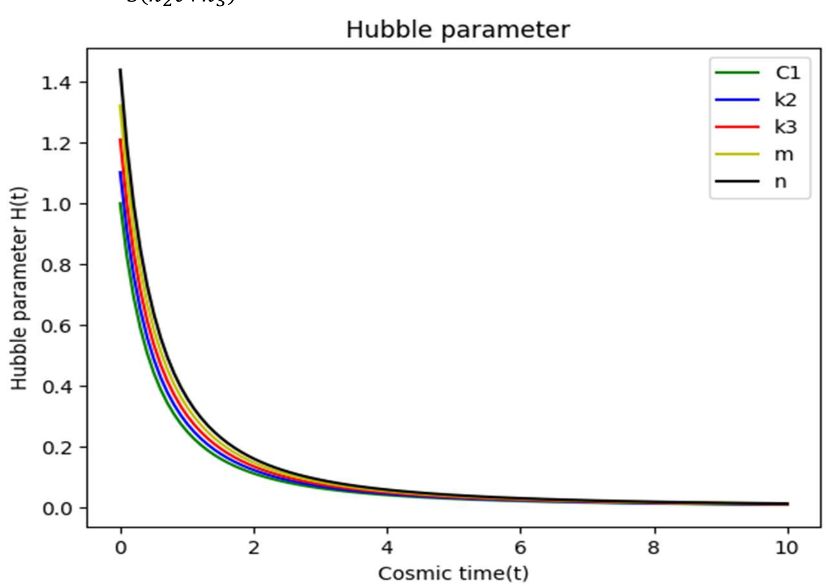

Fig3: Hubble Parameter H(t) versus Cosmic time(t)

Dynamical Scalar expansion:

$$\theta = 3H = \frac{(k_1+1)c_1}{(k_2t+k_3)} \quad (24)$$

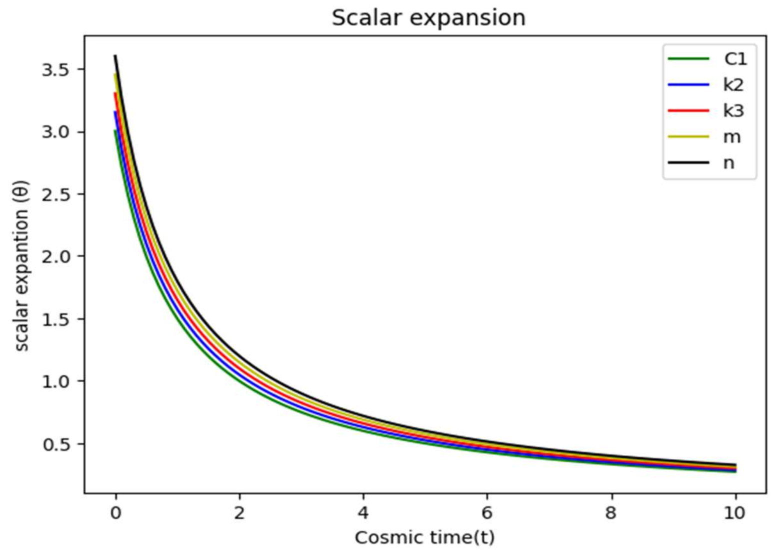

Fig4: Scalar expansion (θ) versus cosmic time (t)

Anisotropic parameter:

$$A_m = \frac{1}{3}\sum_{i=1}^{3}\left(\frac{H_i - H}{H}\right)^2 = \frac{4}{3} \tag{25}$$

Shear scalar:

$$\sigma^2 = \frac{3}{2}A_m H^2 = \frac{2c_1(m+n+1)}{3(k_2 t + k_3)} \tag{26}$$

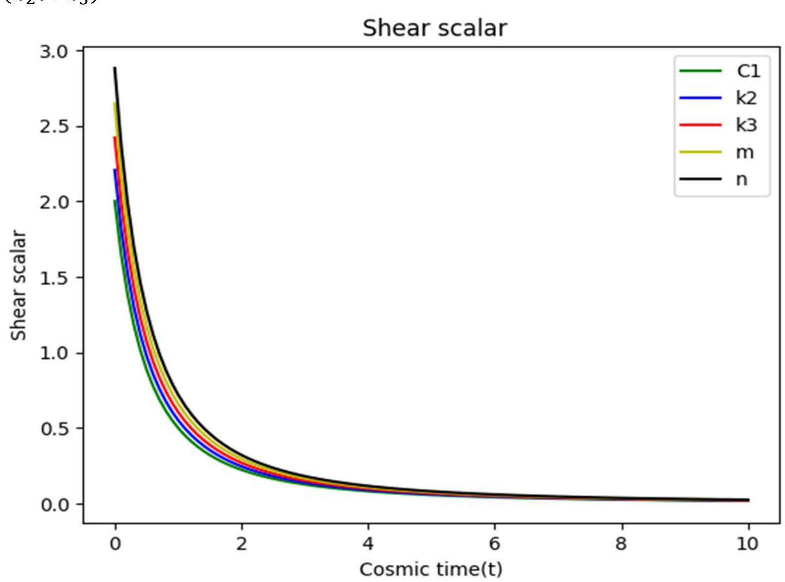

Fig5: Shear scalar (σ^2) versus cosmic time (t)

Deceleration parameter:

$$q = \frac{d}{dt}\left(\frac{1}{H}\right) - 1 = \frac{-3k_2}{C_1(m+n+1)} \tag{27}$$

Substract Equation (8) from (11) and by using equation (12) we have

$$\frac{\dot{A}\dot{B}}{AB} - \frac{\ddot{B}}{B} + \frac{\dot{A}\dot{C}}{AC} - \frac{\ddot{C}}{C} = \frac{8}{3}(\rho - B_c)(4\pi + \mu) \tag{28}$$

From equation (28) we have the value of ρ

$$\rho = \frac{3}{8}\frac{(k_2 t + k_3)^{-2}}{(4\pi + \mu)}\left[m(1+n){c_1}^2 - n(1+n){c_1}^2 - (1+n)(k-1)c_1 k_2\right] + B_c \tag{29}$$

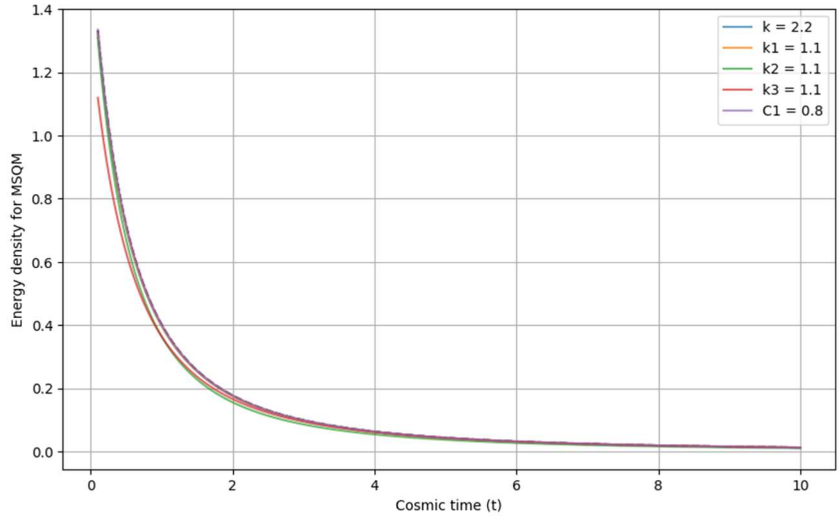

Fig6: Energy density for MSQM (ρ) versus cosmic time (t)

By using equation of state and equation (29) we have

$$p = \frac{1}{8}\frac{(k_2 t + k_3)^{-2}}{(4\pi + \mu)}\{(1+n)[m{c_1}^2 - n{c_1}^2 - (k-1)c_1 k_2]\} - B_C \tag{30}$$

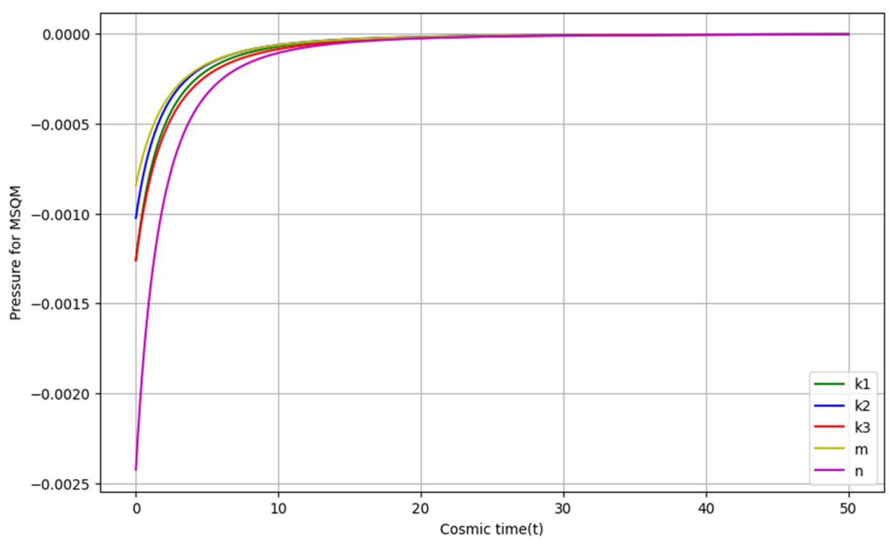

Fig7: Pressure for MSQM (p) versus cosmic time (t)

From equation (8) and (9) we have

$$h^2 = \frac{(k_2 t + k_3)^{-2}}{2(4\pi + \mu)}[(1-m)c_1 k_2 + (1-m)m{c_1}^2 k_1 + n(1-m){c_1}^2 k_1] \tag{31}$$

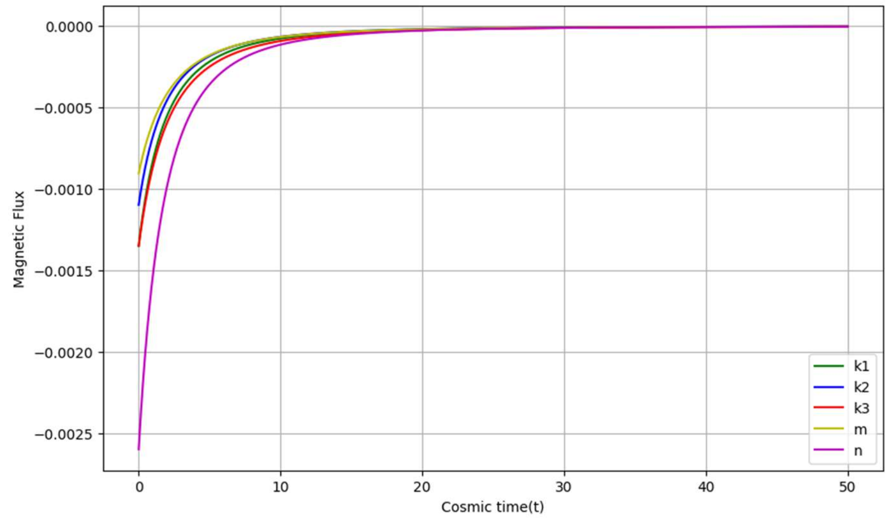

Fig8: Magnetic flux (h^2) versus cosmic time (t)

Adding equation (8) and (9) we have

$$\frac{\ddot{B}}{B}+2\frac{\ddot{C}}{C}+\frac{\dot{B}\dot{C}}{BC}+\frac{\ddot{A}}{A}+\frac{\dot{A}\dot{C}}{AC}=-2(8\pi+3\mu)p+2\mu\rho+2\Lambda \quad (32)$$

By using conditions and substituting the values p and ρ in equation (32) we have

$$\Lambda=\frac{(k_2t+k_3)^{-2}}{2}\left\{[(1+2n+m)(k-1)c_1k_2+n(1+2n+m){c_1}^2+(m^2-m-2)]+\frac{2\pi}{(4\pi+\mu)}[(1+n)m{c_1}^2-(1+n)n{c_1}^2-(1+n)(k-1)k_2c_1]\right\}-4(2\pi+\mu)B_c \quad (33)$$

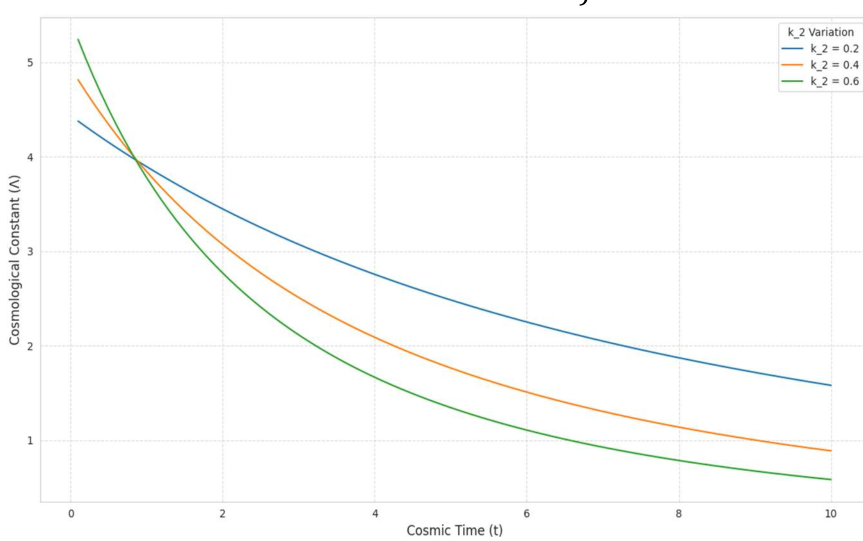

Fig9: Cosmological constant (Λ) versus cosmic time (t)

6. Result and Discussion

Fig1. shows that the graphical behavior of the average scale factor $a(t)$ versus cosmic time (t). The average scale factor increases continuously with cosmic time t. The curve is monotonically increasing and becomes steeper as time t progresses, indicating accelerated expansion of the model universe. At early cosmic time t≈0 for all parameter set k_1, k_2, k_3, m, n, the scale factor grows slowly. As time t increases, the growth rate increases rapidly. The scale factor reaches very large values at later times, showing nonlinear expansion behavior. The positive curvature of the graph confirms that the expansion is accelerating. The model begins with a comparatively small value of the scale factor at early times t=0 and expands rapidly as cosmic time $t \to \infty$.

Fig2. shows the variation of the **spatial volume** (V) with respect to **cosmic time** (t). It increases continuously as cosmic time increases from $t = 0$. The curve exhibits a strong nonlinear growth pattern, indicating a rapidly expanding behavior of the volume parameter. Initially, the increase is gradual, but for larger values of t, the growth becomes much steeper. The overlap of the curves corresponding to the parameters $k, k_1, k_2, k_{3,} m$ *and* n indicates that the chosen parameter values contribute collectively to the same expansion trend.

Fig3. shows that the graphical behavior of **Hubble parameter** $H(t)$ **versus cosmic time** (t) shows that its value is **very high at the beginning of cosmic time** for all parameter choices. As time increases, the Hubble parameter **declines steeply**, and after a short interval, the rate of decrease becomes more gradual, with the curves tending toward **values close to zero** at later times.

The Scalar expansion (θ) with respect to cosmic time t is shown by Fig4. and equation (24) by choosing different values for $c_{1,} k_1, k_2, m, n$. It is decreasing with respect to time t.

Fig5. shows that the graphical behavior of Shear scalar (σ^2) versus cosmic time (t) **and it** decreases over cosmic time t for different parameter choices $c_{1,} k_1, k_2 m, n$. For all parameter sets, the shear scalar is **high at early times near** $t = 0$. It **decreases rapidly** as time increases and for large value of t, the shear scalar **approaches zero** for all cases. Fig6. shows that the energy density for MSQM verses cosmic time t for different parameter choices k_1, k_2, k_3, m, n, B_c. Fig7. **s**hows that the graphical behavior of pressure for Magnetic Strange Quark matter (MSQM) versus cosmic time t for different parametersk_1, k_2, k_3, m, n. Fig8. shows that the Magnetic flux versus cosmic time t for parameter k_1, k_2, k_3, m, n. The graph shows the variation of magnetic flux with cosmic time t for different model parameters k_1, k_2, k_3, m and n. At the initial stage the magnetic flux is negative for all parameter choices, indicating a strong initial magnetic effect. As cosmic time increases, the magnetic flux gradually increases toward zero. Fig9. shows that the graphical behavior of cosmological constant (Λ) versus cosmic time (t) for the different values of k_2 and as $t \to \infty$ the value of $\Lambda = -4(2\pi + \mu)B_c$ is constant.

7. Conclusion

In this paper we have studied Bianchi type-I cosmological model filled with magnetized strange quark matter (MSQM) within the framework of $f(R,T)$ gravitation theory. For the solution of Field equation we have used the EoS of the strange quark matter. We have obtained the solution for Bianchi type-I universe. In all universe model bag constant B_c is effective on pressure, density and cosmological term. In all Bianchi type universe model the density of MSQM increases with the value of Bag constant while the pressure and cosmological term value are decreasing by B_c. For $t \to \infty$ the value of $\Lambda = -4(2\pi + \mu)B_c$ is constant shown by equation (33).

Average scale factor versus cosmic time t is depicted in Fig1. and equation (18) shows that cosmological model successfully describes an accelerating universe. The evolution of the average scale factor shows that the universe expands from an initially smaller state toward a rapidly growing large-scale structure at late times. The accelerated growth of $a(t)$ supports the modern observational picture of cosmic acceleration and is consistent with dark-energy-dominated cosmological behavior. This model provides a physically viable description of late-time cosmic evolution. Also shows that the universe remains expanding for all cosmic time, the expansion rate increases continuously and the model predicts accelerated cosmological dynamics.

Spatial volume versus cosmic time t is represented by Fig2. and described by equation (19) shows that spatial volume is a monotonically increasing function of cosmic time t. This model represents an expanding cosmological system in which the spatial volume grows rapidly with respect to time. The Fig3. and equation (23) shows that the Hubble parameter versus cosmic time t indicates that the universe undergoes a **rapid expansion phase initially**, which slows down significantly over time, leading to a **diminishing expansion rate** that approaches zero in the long-term evolution. The Scalar expansion with respect to cosmic time t is shown by Fig4. and described by equation **(**24) by choosing different values for $c_{1,}k_1, k_2m, n$ and decreases as time progresses. Fig5. and equation (26) represent the shear scalar versus cosmic time t for the different values for $c_{1,}k_1, k_2m, n$. Regardless of parameter choices, the system predicts a universe that becomes **increasingly isotropic with time**, as the shear scalar vanishes asymptotically. Equation (27) represent the deceleration parameter here q is negative for $k_2 < 1$ and it shows that universe is expanding. Fig6. and describe by Equation (29) shows that the energy density for MSQM versus cosmic time t for different parameters k_1, k_2, k_3, m, n, B_c and it shows decreases as time progresses. Fig7. and Equation (30) **s**hows that Pressure for Magnetic Strange Quark matter (MSQM) versus cosmic time t. The pressure profile is negative and increasing which shows that universe is accelerating. Fig8. and equation (31) shows that the Magnetic flux versus cosmic time t for parameter choices k_1, k_2, k_3, m, n. The obtained results indicate that the magnetic flux increases in magnitude as cosmic time progresses and eventually approaches zero at late times. This behavior suggests that the magnetic field was dominant during the early phase of the universe but gradually dissipated due to cosmic expansion. The parameter n produces the strongest initial magnetic effect, whereas the remaining parameters $k_1, k_2, k_3, m \ and \ n$ show comparatively weaker magnetic contributions. Despite the differences in initial magnitude, all models converge to the same long-term behavior, implying that the magnetic flux becomes negligible in the late-time universe. Therefore, the model supports the idea of a rapidly decaying primordial magnetic field and demonstrates the stability of the cosmological system at large cosmic times.

In this model, the magnetic field evolves inversely with the product of the scale factors orthogonal to its direction. Consequently, the magnetic flux remains constant, indicating conservation despite anisotropic expansion. Fig9. and equation (33) shows that cosmological constant versus cosmic time t for the different values of k_2 and as $t \to \infty$ the value of Λ is also tends to infinity. The asymptotic approach of Λ toward a small positive value at large cosmic times is compatible with current observational evidence suggesting the existence of dark energy responsible for the present accelerated expansion of the universe.

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