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The Behaviour of Magnetized Strange Quark Matter on Bianchi VI_h Universe in the Framework of f(R,T) Theory

Sezgin Aygün[1*], Can Aktaş[2] and İhsan Yılmaz[3]

[1] *Department of Physics, Çanakkale Onsekiz Mart University, Arts and Sciences Faculty, Terzioğlu Campus, 17020, Turkey.*
[2] *Department of Mathematics, Çanakkale Onsekiz Mart University, Arts and Sciences Faculty, Terzioğlu Campus, 17020, Turkey.*
[3] *Department of Computer Engineering, Çanakkale Onsekiz Mart University, Engineering Faculty, Terzioğlu Campus, 17020, Turkey.*

Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

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ABSTRACT

In this paper we have investigated Bianchi VI_h universe model with magnetized strange quark matter (MSQM) distribution in $f(R,T)$ gravity. For the solutions of modified field equations we have used the EoS of strange quark matter and anisotropy parameter with $\alpha = 1, -1, 0$ in Bianchi VI_h universe. We get magnetic field for $\alpha = -1$ parameter but we obtain $h^2 = 0$ for $\alpha = 1$ and $\alpha = 0$ parameters in Bianchi VI_h models. At the end of time, we get dark energy model for $\alpha = 1$ and $\alpha = 0$ models i.e. we get $\rho = -p = B_c$. We conclude that the source of cosmological !term may be

*Corresponding author: E-mail: saygun@comu.edu.tr;

SQM i.e. the source of dark energy may be SQM. These results agree with the solutions of Aktaş and Aygün also Aygün et al. in $f(R,T)$ theory. Also, we get magnetized strange quark matter distribution in Einstein's general relativity theory with Λ for this model.

Keywords: Strange quark matter; bianchi VI_h; f(R,T) theory; magnetic field.

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1 INTRODUCTION

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 [3] and etc. 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 $f(R,T) = f_1(R) + f_2(R)f_3(T)$, 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],[5],[6],[7],[8],[9],[10],[11],[12],[13],[14],[15],[16].

Although the origin of the magnetic field is still unknown, magnetic fields have significant role in the early universe [17]. In this research we have investigated MSQM in $f(R,T)$ theory for Bianchi type VI_h universe model due to following reasons; When $T \approx 200$ MeV, the "Quark Gluon Plasma-hadron gas phase transition" has occurred in the early universe. On the strength of β-equilibrium, quark-gluon matter should meet charge neutrality [18],[19],[20]. Also in quantum chromodynamics electric field of quark matter vanishes because of Ohms Law [18], [21]. 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:

$$p = \frac{\rho - 4B_c}{3} \tag{1.1}$$

here B_c is bag constant [22],[23]. Also, this constant is given between diverse values. The Bag constant B_c has been described the range of $60 - 80\ MeV(fm)^3$ by Chakraborty et al.[24],[25].

In this context, Aygün et al. have researched SQM solutions for Marder type universe model in $f(R,T)$ theory [26]. Also, Aktaş and Aygün have investigated MSQM distribution for FRW universe model in $f(R,T)$ gravity [27]. However, Agrawal and Pawal have studied quark and SQM for plane symmetric cosmological model in $f(R,T)$ gravity [28]. Sahoo et al. [29] have researched MSQM dynamics in $f(R,T)$ gravity. Çağlar and Aygün [30] have investigated Bianchi type I universe model with quark matter distributions in $f(R,T)$ gravity theory. Bianchi universe models have widely been researched in Einstein's theory also alternative gravitation theories to debate anisotropic form of the universe [9]. The homogeneous and anisotropic universe models play an important role in describing the behavior of the universe. Also, Bianchi type cosmological models are so significant because they are homogeneous and anisotropic.

Recently, Mishra and Sahoo [31] have studied Bianchi type VI_h universe model in $f(R,T)$ gravity. There are not many studies in the literature on Bianchi type VI_h metric in modified theories. Then, in this study we have investigated MSQM distribution for Bianchi VI_h universe in $f(R,T)$ gravitation theory. The paper is organization as follows: In section 2, we have represented $f(R,T)$ theory and its solutions for $\alpha = 1, -1, 0$ respectively. Also, in the last section we gave conclusions.

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

$f(R,T)$ theory. The action of this theory is given by

$$S = \int \left(\frac{f(R,T)}{16\pi G} + L_m \right) \sqrt{-g} d^4x \qquad (2.1)$$

In this theory R is given by Ricci scalar, T is defined by the trace of $T_{\alpha\beta}$, g is the determinant of $g_{\alpha\beta}$ also $f(R,T)$ is the arbitrary function of R and T. Also, L_m indicates Lagrangian [3]. $T_{\alpha\beta}$ is defined as [3]

$$T_{\alpha\beta} = g_{\alpha\beta} L_m - \frac{2\partial L_m}{\partial g^{\alpha\beta}} \qquad (2.2)$$

By varying equation (2.1), we obtain following equality

$$f_R(R,T) R_{\alpha\beta} - \frac{1}{2} f(R,T) g_{\alpha\beta} + (g_{\alpha\beta}\Box - \nabla_\alpha \nabla_\beta) f_R(R,T) = 8\pi T_{\alpha\beta} - f_T(R,T) T_{\alpha\beta} - f_T(R,T) \Xi_{\alpha\beta} + \Lambda g_{\alpha\beta} \qquad (2.3)$$

where $f_R(R,T)$ and $f_T(R,T)$ show derivatives of $f(R,T)$ with respect to R and T respectively and ∇_α is the covariant derivative; $\Box = \nabla_\alpha \nabla^\alpha$ [3]. Here $\Xi_{\alpha\beta}$ is defined by

$$\Xi_{\alpha\beta} = -2T_{\alpha\beta} - p g_{\alpha\beta} \qquad (2.4)$$

For the solutions of modified $f(R,T)$ gravity theory Harko et al. [3] suggested three $f(R,T)$ models as follows

$$f(R,T) = \begin{cases} R + 2f(T) \\ f_1(R) + f_2(T) \\ f_1(R) + f_2(R) f_3(T) \end{cases} \qquad (2.5)$$

In this study to obtain exact solutions of $f(R,T)$ gravity theory, we will examine the first model of Harko et al. i.e. $f(R,T) = R + 2f(T)$ for MSQM in Bianchi VI_h universe model with Λ. Bianchi VI_h space-time universe model is given by

$$ds^2 = dt^2 - A^2 dx^2 - B^2 e^{2x} dy^2 - C^2 e^{2\alpha x} dz^2 \qquad (2.6)$$

here A, B and C are functions of t and $\alpha = \pm 1, 0$ [31]. In this study, we consider the source of gravitation as MSQM. The energy momentum tensor of MSQM distribution is defined by [21].

$$T_{\alpha\beta} = (p + \rho + h^2) u_\alpha u_\beta - \left(p + \frac{h^2}{2}\right) g_{\alpha\beta} - h_\alpha h_\beta \qquad (2.7)$$

where 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 $u^i h_i = 0$ [18]. The equations of $f(R,T)$ gravitation theory are given by[3]

$$G_{\alpha\beta} = [8\pi + 2f'(T)] T_{\alpha\beta} + [2pf'(T) + f(T) + \Lambda] g_{\alpha\beta} \qquad (2.8)$$

here $f'(T) = \frac{df(T)}{dT}$. If we choice $f(T) = \mu T$ the equation (2.8) takes the form

$$G_{\alpha\beta} = [8\pi + 2\mu] T_{\alpha\beta} + [2\mu p + \mu T + \Lambda] g_{\alpha\beta} \qquad (2.9)$$

where μ is a constant and the trace of energy-momentum tensor is given by $T = \rho - 3p$. Then modified field equations of $f(R,T)$ theory are given by

$$\frac{\ddot{B}}{B} + \frac{\ddot{C}}{C} + \frac{\dot{B}\dot{C}}{BC} - \frac{\alpha}{A^2} = (4\pi + \mu) h^2 - (8\pi + 3\mu) p + \mu\rho + \Lambda \qquad (2.10)$$

$$\frac{\ddot{A}}{A} + \frac{\ddot{C}}{C} + \frac{\dot{A}\dot{C}}{AC} - \frac{\alpha^2}{A^2} = -(4\pi + \mu) h^2 - (8\pi + 3\mu) p + \mu\rho + \Lambda \qquad (2.11)$$

$$\frac{\ddot{A}}{A} + \frac{\ddot{B}}{B} + \frac{\dot{A}\dot{B}}{AB} - \frac{1}{A^2} = -(4\pi + \mu) h^2 - (8\pi + 3\mu) p + \mu\rho + \Lambda \qquad (2.12)$$

$$\frac{\dot{A}\dot{B}}{AB} + \frac{\dot{B}\dot{C}}{BC} + \frac{\dot{A}\dot{C}}{AC} - \frac{1}{A^2}(\alpha^2 + \alpha + 1) = (4\pi + \mu) h^2 + (8\pi + 3\mu)\rho - p\mu + \Lambda \qquad (2.13)$$

$$\alpha\left(\frac{\dot{A}}{A}-\frac{\dot{C}}{C}\right)+\frac{\dot{A}}{A}-\frac{\dot{B}}{B}=0 \tag{2.14}$$

also, the kinematical quantities of Bianchi VI_h universe model like as shear scalar, expansion scalar and Hubble parameter are given as

$$\sigma^2=\frac{1}{3}\left(\left(\frac{\dot{A}}{A}\right)^2+\left(\frac{\dot{B}}{B}\right)^2+\left(\frac{\dot{C}}{C}\right)^2-\frac{\dot{A}\dot{B}}{AB}-\frac{\dot{A}\dot{C}}{AC}-\frac{\dot{B}\dot{C}}{BC}\right) \tag{2.15}$$

$$\theta=\frac{\dot{A}}{A}+\frac{\dot{B}}{B}+\frac{\dot{C}}{C} \tag{2.16}$$

$$H=\frac{1}{3}\left(\frac{\dot{A}}{A}+\frac{\dot{B}}{B}+\frac{\dot{C}}{C}\right) \tag{2.17}$$

In this study we have seven unknowns A, B, C ρ, p, h^2, Λ and five $f(R,T)$ field equations. In order to solve the system completely we use the conditions equation of state (EoS) of MSQM as $p=\frac{\rho-4B_c}{3}$ and anisotropy parameter as $\frac{\sigma}{\theta}$. In three subsection, we will obtain $f(R,T)$ gravitation theory solutions for MSQM with Λ in Bianchi type VI_h universe for $\alpha=1$, $\alpha=-1$ and $\alpha=0$ respectively.

2.1 $f(R,T)$ Gravitation Theory Solutions in Bianchi VI_h Universe for $\alpha=1$

Using equation (2.14) with the condition of $\alpha=1$, we obtain A metric potential related with B and C as follows

$$A=\sqrt{BC} \tag{2.18}$$

Using equation (2.18) and anisotropy parameter, $\frac{\sigma}{\theta}=\xi$ here $0\leq\xi\leq1$, we get B metric potential as follows

$$B=C^{-\frac{3\xi-1}{3\xi+1}} \tag{2.19}$$

If we use equation (1.1), (2.18) and (2.19) in equations (2.10)-(2.13), we obtain all metric potentials as follows

$$A=\left(\frac{at+b}{3\xi+1}\right)^{\frac{1}{3}} \tag{2.20}$$

$$B=\left(\frac{at+b}{3\xi+1}\right)^{\frac{1-3\xi}{3}} \tag{2.21}$$

$$C=\left(\frac{at+b}{3\xi+1}\right)^{\frac{3\xi+1}{3}} \tag{2.22}$$

here a and b are integration constants. Using equations (1.1), (2.10)-(2.13), (2.15), (2.16) and (2.20)-(2.22), we get the pressure, energy density and the value of magnetic field of MSQM distribution also cosmological term as follows

$$p=\frac{(1-3\xi^2)a^2}{12(4\pi+\mu)(at+b)^2}-\frac{(3\xi+1)^{\frac{2}{3}}}{4(4\pi+\mu)(at+b)^{\frac{2}{3}}}-B_c \tag{2.23}$$

$$\rho=\frac{(1-3\xi^2)a^2}{4(4\pi+\mu)(at+b)^2}-\frac{3(3\xi+1)^{\frac{2}{3}}}{4(4\pi+\mu)(at+b)^{\frac{2}{3}}}+B_c \tag{2.24}$$

$$h^2=0 \tag{2.25}$$

and

$$\Lambda=\frac{(2\pi+\mu)(3\xi^2-1)a^2}{3(4\pi+\mu)(at+b)^2}-\frac{(6\pi+\mu)(3\xi+1)^{\frac{2}{3}}}{(4\pi+\mu)(at+b)^{\frac{2}{3}}}-4(2\pi+\mu)B_c \tag{2.26}$$

2.2 $f(R,T)$ Gravitation Theory Solutions in Bianchi VI_h Universe for $\alpha = -1$

Using equation (2.14) with the condition of $\alpha = -1$, we obtain B metric potential related with C as follows

$$B = mC \tag{2.27}$$

here m is integration constant. Without loss of generality we can take $m = 1$ and we get $B = C$ in Bianchi VI_h universe model. Using equation (2.27) and anisotropy parameter (eq. (2.15) and (2.16)), we get the value of C metric potential as follows

$$C = A^{\frac{\sqrt{3}-3\xi}{\sqrt{3}+6\xi}} \tag{2.28}$$

If we use equation (1.1), (2.27) and (2.28) in equations (2.10)-(2.13), we obtain A, B and C metric potentials as follows

$$A = c_1 \tag{2.29}$$

$$B = c_1^{\frac{\sqrt{3}-3\xi}{\sqrt{3}+6\xi}} \tag{2.30}$$

$$C = c_1^{\frac{\sqrt{3}-3\xi}{\sqrt{3}+6\xi}} \tag{2.31}$$

here c_1 is integration constant. Using equations (1.1), (2.10)-(2.13), (2.15), (2.16) and (2.29)-(2.31), we obtain the pressure, energy density and the value of magnetic field of MSQM distribution also cosmological term for $\alpha = -1$ as follows

$$p = -\frac{1}{4(4\pi+\mu)c_1^2} - B_c = -\frac{H^2}{4} - B_c \tag{2.32}$$

$$\rho = -\frac{3}{4(4\pi+\mu)c_1^2} + B_c = -\frac{3H^2}{4} + B_c \tag{2.33}$$

$$h^2 = \frac{1}{(4\pi+\mu)c_1^2} \tag{2.34}$$

and

$$\Lambda = -\frac{2\pi}{(4\pi+\mu)c_1^2} - 4(2\pi+\mu)B_c \tag{2.35}$$

2.3 $f(R,T)$ Gravitation Theory Solutions in Bianchi VI_h Universe for $\alpha = 0$

In this subsection, we have obtained exact solutions of $f(R,T)$ theory only the special value of ξ. Because we obtained exact solutions for the free parameter ξ in the first and second subsections for $\alpha = 1$ and $\alpha = -1$. But in this subsection the solutions of the modified field equations were only obtained for the $\xi = \frac{\sqrt{3}}{6} = 0.29$. So we have used this special value for these solutions. This value of ξ is also in agreement with the definition range of $0 \leq \xi \leq 1$. Using $\xi = \frac{\sqrt{3}}{6} = 0.29$ and equation (2.14) with the value of $\alpha = 0$, we get A metric potential related with B as follows

$$A = nB \tag{2.36}$$

here n is integration constant. Without loss of generality we can take $n = 1$. Using equation (2.36) and anisotropy parameter, we get C metric potential as follows

$$C = B^{\frac{\sqrt{3}-6\xi}{\sqrt{3}+3\xi}} \tag{2.37}$$

If we use equation (1.1), (2.36) and (2.37) in equations (2.10)-(2.13), we obtain all the metric potentials as follows

$$A = \sqrt{t^2 - 2c_2t + 2c_3} \tag{2.38}$$

$$B = \sqrt{t^2 - 2c_2t + 2c_3} \tag{2.39}$$

$$C = 1 \tag{2.40}$$

here c_2 and c_3 are integration constants. With the help of equations (1.1), (2.10)-(2.13), (2.15), (2.16) and (2.38)-(2.40), we get the pressure, energy density and the value of magnetic field of MSQM distribution also cosmological term for $\alpha = 0$ as follows

$$p = -\frac{c_2^2 - 2c_3}{4(4\pi+\mu)(t^2-2c_2t+2c_3)^2} - B_c \tag{2.41}$$

$$\rho = -\frac{3(c_2^2 - 2c_3)}{4(4\pi+\mu)(t^2-2c_2t+2c_3)^2} + B_c \tag{2.42}$$

$$h^2 = 0 \tag{2.43}$$

and

$$\Lambda = \frac{2(2\pi + \mu)(c_3 - 8\pi - 2\mu)}{(4\pi + \mu)(t^2 - 2c_2 t + 2c_3)^2} - \frac{(2\pi + \mu)c_2^2}{4(t^2 - 2c_2 t + 2c_3)^2} - 4(2\pi + \mu)B_c \tag{2.44}$$

3 CONCLUSIONS

In this study we have investigated Bianchi VI_h universe model with magnetized strange quark matter distribution in $f(R,T)$ gravitation theory. For the solutions of modified field equations we have used the EoS of strange quark matter and anisotropy parameter with $\alpha = 1, -1, 0$ in Bianchi VI_h universe. We have obtained three solutions of Bianchi VI_h universe model. In all universe models bag constant B_c is effective on pressure, density and cosmological term. In all three Bianchi VI_h universe models the density of MSQM distribution increases with the value of Bag constant while the pressure and cosmological term value are decreasing by B_c. However, magnetic field is effective only $\alpha = -1$ parameter but we get $h^2 = 0$ for $\alpha = 1$ and $\alpha = 0$ in Bianchi VI_h models.For $t \to \infty$, we get dark energy ($\rho = -p = B_c$) model for $\alpha = 1$ and $\alpha = 0$ models. And also, we find $\Lambda = -4(2\pi + \mu)B_c$. From above results we conclude that the source of cosmological term may be SQM i.e. the source of dark energy may be SQM. These results agree with the solutions of Aktaş and Aygün [27] and also, Aygün et al. [26] in $f(R,T)$ theory. Aktaş and Aygün [27] have investigated FRW universe. Also, they have researched MSQM and SQM in $f(R,T)$ theory and they obtained dark energy (DE) solutions ($p = -B_c$ and $\rho = B_c$) for all $f(R,T)$ models of Harko et al. However these results agree with the studies of Yilmaz et al. [32] in f(R) theory for Bianchi types I and V models and Sahoo et al. [25] in $f(R,T)$ theory for LRS Bianchi type I universe model. From these results, it could be said that for $t \to \infty$, SQM may be the source of DE in homogeneous and anisotropic universe models for different gravitation theories. In this study again we obtained the relation dark energy and bag constant in $f(R,T)$ theory. SQM could give an idea of existence of DE in the universe and this result supports observations of SNIa [33]. It is interesting that we obtain constant value for metric potentials, pressure, density, h^2 and Λ in $\alpha = -1$ model. Also we have achieved a relationship between pressure, density and magnetic field. The pressure and density of MSQM are decreasing with magnetic field in equations (see (2.32) and (2.33)). However, if we take $\mu = 0$ in three Bianchi VI_h universe models, we find magnetized strange quark matter distribution in Einstein's general relativity theory with Λ.

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