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Bianchi Type-III Model in the Presence of Electromagnetic Field with Lyra Geometry in Modified Gravity

Dr. Ravikant D Mishra [1*], Dr. Vinay P Tripade [2]
[1] Assistant Professor, Bhiwapur Mahavidyalaya Bhiwapur, Maharashtra, India
[2] Assistant Professor, Sarvodaya Mahavidyalaya Sindewahi, Maharashtra, India

Corresponding Author: **Dr. Ravikant D Mishra**

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Abstract
This paper is studied to the study of Bianchi type-III cosmological model with $f(R,T)$ gravity in the presence of electromagnetic field based on Lyra geometry. We formalize the $f(R,T)$ gravity equations based on Lyra geometry. To solve the field equations, obtained by considering Bianchi type-III space-time, we used physical condition that the shear scalar σ^2 is proportional to scalar expansion θ. The behavior of the model has been discussed by studying the physical and kinematical properties of the model.

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Introduction

In the explain of cosmological models, anisotropic Bianchi-type universes provide an important extension beyond the highly symmetric Friedmann–Lemaître–Robertson–Walker (FLRW) model. Among them, the Bianchi Type-V space–time is significantly as it represents a spatial homogeneous but anisotropic model with negative curvature often considered a generalization of open FLRW universe. Such models allow for a more detailed description of the early Universe, where anisotropies and non-equilibrium processes may have played a significant role before universe evolved toward the nearly isotropic state observed today.

Bianchi universe models are spatially homogeneous that in general are anisotropic. Due to this, Bianchi type models are important in which the process of isotropization of the universe is studied through the passage of time.

Adhav K.S. [1] studied the exact solutions of $f(R,T)$ field equations for exact solutions of Bianchi type-I space-time. Farasat Shamir M. et.al. [2] obtained the exact solutions of Bianchi type I & V model $f(R,T)$ gravity by using constant deceleration parameter. Reddy D.R.K.et.al. [3] Examined the LRS Bianchi type-II universe in $f(R,T)$ theory.

Kumar and Singh [4] discussed Bianchi type-I space-time in general relativity in presence of the perfect fluid. Singh and Baghel [5] examined Bianchi type-V cosmological model with Bulk Viscosity. Kiran M. et.al. [6] Examined non-existence of Bianchi type-III Bulk viscous string cosmological model in $f(R,T)$ gravity. Goswami et.al. [7] studied modeling of accelerating universe with bulk viscous fluid in Bianchi type-V space-time. Sahoo P. and Reddy R. (2018) [8] studied LRS Bianchi type-I bulk viscous cosmological model in $f(R,T)$ theory of gravity. Singh J.P. [9] studied Bianchi type-V cosmological model with time dependent-Λ. Tiwari L.K. et.al. [10] studied Bianchi type-V cosmological model with viscous fluid and varying Λ. Also, Tiwari R.K. explained phase transition of LRS Bianchi type-I cosmological model in $f(R,T)$ gravity. H.R. Ghate et.al. [11] studied Bianchi type-IX viscous stringing cosmological model in $f(R,T)$ gravity.

Bianchi type-III cosmological model in Lyra geometry in the presence of massive scalar field by Singh J.K. et.al. [12] Maurya D.C. [13] investigated modified $f(R,T)$ cosmology with observational constraint in Lyra Geometry. Hegazy E.A[14] discussed Bulk viscous Bianchi type-I cosmological model in Lyra geometry and in general theory of relativity.

Desikan K. [15] explained cosmological models in Lyra Geometry with time varying displacement field. Ram S. et.al. [16] studied Kantowski Sachs cosmological model with anisotropic dark energy in Lyra Geometry and recently Bishnu Prasad Bramha et.al. [17] studied bulk viscous Bianchi type-V cosmological model in $f(R,T)$ gravity. Above investigation motivate us to study the Biancy type-III cosmological model in $f(R,T)$ gravity with perfect fluid as matter source based on Lyra geometry.
."Recent high-precision observational data indicate that our universe is undergoing an accelerated expansion (Riess *et al.* [18]; Perlmutter *et al.* [19]). In addition, CMB radiation (Spergel *et al.* [20]) and large-scale structure surveys (Tegmark *et al.* [21]) also provide indirect evidence for this late-time cosmic acceleration. The phenomenon is generally attributed to the front of a mysterious component, termed *dark energy*. In this context, Nojiri and Odintsov [22] proposed a general framework for unifying the matter-dominated era with accelerated epoch within scalar–tensor theories and dark fluid models. Furthermore, Nojiri and Odintsov [23] discussed a comprehensive review of modified gravity theories, which have emerged as a viable gravitational alternative to explain dark energy."
In the present work, we focus on the construction and analysis of a Bianchi Type-III model in the region of electromagnetic field and a bulk viscous fluid in modified gravity theory. The study emphasizes the effect of matter and fields on evolution of cosmological model. Insights from this work may contribute to a better understanding both the early anisotropic universe and the mechanisms driving the present cosmic acceleration.
The paper is organized as follows: In section II, formalism of $f(R,T)$ gravity based on Lyra geometry. In section III, we discuss metric and field equations. Solution of the field equations is given in section IV physical and kinematical properties in section V and in last section discussion and conclusion.

Lyra's geometry and modified $f(R,T)$ gravity
The curvature tensor of Lyra geometry is given by

$$\tilde{R}^i_{j\rho\sigma} = A^{-2}\left[\frac{\partial}{\partial x^\rho}\left(A\hat{\Gamma}^i_{j\sigma}\right) - \frac{\partial}{\partial x^\sigma}\left(A\hat{\Gamma}^i_{j\rho}\right) + A^2\left(\hat{\Gamma}^i_{\lambda\rho}\hat{\Gamma}^\lambda_{j\sigma} - \hat{\Gamma}^i_{\lambda\sigma}\hat{\Gamma}^\lambda_{j\rho}\right)\right] \quad (1)$$

where $\hat{\Gamma}^i_{j\sigma} = \tilde{\Gamma}^i_{j\sigma} - \frac{1}{2}\delta^i_j\varphi_\sigma$ which is not symmetric with respect to j and σ. In Lyra geometry, unlike Weyl geometry, the connection is metric preserving as in Riemannian geometry which indicates that length transfers are integrable. Then, the curvature scalar of Lyra geometry will be

$$\tilde{R} = A^{-2}R + 3A^{-1}\nabla_i\varphi^i + \frac{3}{2}\varphi^i\varphi_i + 2A^{-1}(logA^2\quad)_{,i}\,\varphi^i \quad (2)$$

Where $\varphi^i = g^{ij}\varphi_j$ is calleddisplacement vectors field of Lyra geometry and R is the Riemannian curvature scalar
The action for $f(R,T)$ theory of gravity using Lyra geometry is given as

$$S = \frac{1}{16\pi G}\int f(\tilde{R},T)\sqrt{-g}d^4x + \int L_m\sqrt{-g}d^4x, \quad (3)$$

Using A = 1 and $L = \tilde{R}$ through the equation (2) results in

$$\tilde{R} = R + 3\nabla_i\varphi^i + \frac{3}{2}\varphi^i\varphi_i \quad (4)$$

Where $\tilde{R}, T, g$ and L_m are function the Ricci scalar, the trace of the stress-energy tensor of matter T_{ij}, the determinant of the metric tensor g_{ij} and the matter Lagrangian density respectively.
The stress-energy tensor of matter is defined as

$$T_{ij} = -\frac{2}{\sqrt{-g}}\frac{\delta(\sqrt{-g}L_m)}{\delta g^{ij}}, \quad (5)$$

and its trace is given by $T = g^{ij}T_{ij}$.
Assuming that the Lagrangian density L_m of matter depends only on the components of the metric tensor g_{ij} rather than its derivatives. Hence, we obtain

$$T_{ij} = g_{ij}L_m - 2\frac{\partial L_m}{\partial g^{ij}}, \quad (6)$$

Varying the action S with respect to the metric tensor g_{ij}, the field Equations in $f(R,T)$ theory of gravity are given by

$$f_{\tilde{R}}(\tilde{R},T)\tilde{R}_{ij} - \frac{1}{2}f(\tilde{R},T)g_{ij} - (\nabla_i\nabla_j - g_{ij})$$
$$f_{\tilde{R}}(\tilde{R},T) = -\frac{8\pi G}{c^2}T_{ij} - f_T(\tilde{R},T)(T_{ij} + \Theta_{ij}), \quad (7)$$

Where$\Theta_{ij} = -2T_{ij} + g_{ij}L_m - 2g^{lm}\frac{\partial^2}{\partial g^{ij}\partial g^{lm}}$ (8)

Here $f_{\tilde{R}}(\tilde{R},T) = \frac{\partial f(\tilde{R},T)}{\partial \tilde{R}}, f_T(\tilde{R},T) = \frac{\partial f(\tilde{R},T)}{\partial T}$,$\Box \equiv \nabla^i \nabla_i$
where$\nabla_i$is covariant derivatives.
If the matter is treated as perfect fluid, then T_{ij} for bulk viscous fluid in connection with an electromagnetic field is

$$T_{ij} = (\bar{p} + \rho)u_i u_j - \bar{p}g_{ij} - E_{ij} \quad (9)$$

Where $\bar{p} = p - 3\xi H = \omega\rho$
We considerρ, $\bar{p}$and $\xi(t)$ are function of t.here $\bar{p}$is the total pressure which includes the proper pressure p,ρbe the rest energy density of the matter, $\xi(t)$ denoted as the coefficient of Bulk viscosity, $3\xi H$is generally known as Bulk viscous pressure, $E_{ij}$is Electromagnetic energy tensor defines as

$$E_{ij} = -F_{ir}F^{kr}g_{kj} + \frac{1}{4}F_{ab}F^{ab}g_{ij} \quad (10)$$

The bulk viscous fluids described by an energy density four velocity vector is$u^i = (0,0,0,1)$ in the co-moving co-ordinate system satisfying the condition $u_i u^i = 1$and $u_i \nabla_j u^i = 0$. Since there is no any unique definition of matter Lagrangian. Thus, we can assume$L_m = -\bar{p}$, which gives

$$\Theta_{ij} = -2T_{ij} - \bar{p}g_{ij}, \quad (11)$$

Since the field equations in $f(R,T)$ gravity also depend on the physical nature of the matter field through the tensor g_{ij}, we obtain several models for each choice of f.Three explicit specification of the functional form $f$has been considered in Harko et. al. Constructed the one frame of $f(\tilde{R},T)$ gravity as follows:

$$f(\tilde{R},T) = f_1(\tilde{R}) + f_2(T) \quad (12)$$

Using equations (12), the field Equations (7) can be written as

$$f_{\tilde{R}}(\tilde{R},T)\tilde{R}_{ij} - \frac{1}{2}f_1(\tilde{R},T)g_{ij} - (\nabla_i \nabla_j - g_{ij}\Box)f'_1(\tilde{R},T) = -\frac{8\pi G}{c^2}T_{ij} + f'_2(T)T_{ij} + \left[f'_2(T)p + \frac{1}{2}f_2(T)\right]g_{ij} \quad (13)$$

In this case $f(\tilde{R},T)$ gravity field equation for perfect fluid matter by assuming $f_1 = \lambda\tilde{R} and f_2 = \lambda T$where $\lambda$is taken as arbitrary constant.
The Einstein's field equations (13), reduce to obtained

$$\tilde{R}_{ij} - \frac{1}{2}\tilde{R}g_{ij} = -\left(\frac{8\pi G - \lambda c^2}{\lambda c^2}\right)T_{ij} + \left[p + \frac{1}{2}T\right]g_{ij} \quad (14)$$

Inserting equation (14) by using equation (4),we obtain field equations in Lyra geometry as given by

$$\tilde{R}_{ij} - \frac{1}{2}Rg_{ij} + \frac{3}{2}\phi_i\phi_j - \frac{3}{4}g_{ij}\phi_i\phi^j = -\mu T_{ij} + \left[p + \frac{1}{2}T\right]g_{ij} \quad (15)$$

Where$\varphi^j = (0,0,0,\beta(t))$is displacement vectors field and
$\mu = \frac{8\pi G - \lambda c^2}{\lambda c^2}$is called scale factor.

Metric and field equation
We observed the Bianchi type-III space time whose metric is

$$ds^2 = dt^2 - A^2(t)dx^2 - e^{-2ax}B^2(t)dy^2 - C^2(t)dz^2 \quad (16)$$

Here the metric potential$A$, B and $C$are function of time t and $a$is treated as constant.
Solving field equation (15) with (10), and metric (16) gives following equation

$$\frac{\ddot{B}}{B} + \frac{\ddot{C}}{C} + \frac{\dot{B}\dot{C}}{BC} + \frac{3}{4}\beta^2 = \frac{(16\pi + 3\lambda_2)}{2\lambda_1}\bar{p} - \frac{\lambda_2\rho}{2\lambda_1} + \frac{(F_{13})^2 e^{-2mx}}{2A^2C^2}\left[\frac{(8\pi + 3\lambda_2)}{2\lambda_1}\right] \quad (17)$$

$$\frac{\ddot{A}}{A}+\frac{\ddot{C}}{C}+\frac{\dot{A}\dot{C}}{AC}+\frac{3}{4}\beta^2=\frac{(16\pi+3\lambda_2)}{2\lambda_1}\bar{p}-\frac{\lambda_2\rho}{2\lambda_1}+\frac{(F_{13})^2e^{-2mx}}{2A^2C^2}\left[\frac{(8\pi+3\lambda_2)}{2\lambda_1}\right] \quad (18)$$

$$\frac{\ddot{A}}{A}+\frac{\ddot{B}}{B}+\frac{\dot{A}\dot{B}}{AB}+\frac{3}{4}\beta^2-\frac{\alpha^2}{A^2}=\frac{(16\pi+3\lambda_2)}{2\lambda_1}\bar{p}-\frac{\lambda_2\rho}{2\lambda_1}+\frac{(F_{13})^2e^{-2mx}}{2A^2C^2}\left[\frac{(8\pi+3\lambda_2)}{2\lambda_1}\right] \quad (19)$$

$$\frac{\dot{A}\dot{B}}{AB}+\frac{\dot{A}\dot{C}}{AC}+\frac{\dot{B}\dot{C}}{BC}+\frac{3}{4}\beta^2-\frac{\alpha^2}{A^2}=\frac{(16\pi+3\lambda_2)}{2\lambda_1}\rho-\frac{\lambda_2\bar{p}}{2\lambda_1}+\frac{(F_{13})^2e^{-2mx}}{2A^2C^2}\left[\frac{(8\pi+3\lambda_2)}{2\lambda_1}\right] \quad (20)$$

$$\frac{\dot{A}}{A}-\frac{\dot{B}}{B}=0 \quad (21)$$

Solutions of the field Equations

Integrate equation (21), we get

$A=Bk$ Where $k$is integrating constant

Without loss of generality $k$can be selected as unity

$$A=B \quad (22)$$

Solution of the equation (17) to (20) reduced into independent equation is given as

$$\frac{\ddot{B}}{B}+\frac{\ddot{C}}{C}+\frac{\dot{B}\dot{C}}{BC}+\frac{3}{4}\beta^2=\frac{(16\pi+3\lambda_2)}{2\lambda_1}\bar{p}-\frac{\lambda_2\rho}{2\lambda_1}+\frac{(F_{13})^2e^{-2mx}}{2A^2C^2}\left[\frac{(8\pi+3\lambda_2)}{2\lambda_1}\right] \quad (23)$$

$$2\frac{\ddot{B}}{B}+\frac{\dot{B}^2}{B^2}+\frac{3}{4}\beta^2-\frac{\alpha^2}{B^2}=\frac{(16\pi+3\lambda_2)}{2\lambda_1}\bar{p}-\frac{\lambda_2\rho}{2\lambda_1}+\frac{(F_{13})^2e^{-2mx}}{2A^2C^2}\left[\frac{(8\pi+3\lambda_2)}{2\lambda_1}\right] \quad (24)$$

$$\frac{\dot{B}^2}{B^2}+2\frac{\dot{B}\dot{C}}{BC}+\frac{3}{4}\beta^2-\frac{\alpha^2}{B^2}=\frac{(16\pi+3\lambda_2)}{2\lambda_1}\rho-\frac{\lambda_2\bar{p}}{2\lambda_1}+\frac{(F_{13})^2e^{-2mx}}{2A^2C^2}\left[\frac{(8\pi+3\lambda_2)}{2\lambda_1}\right] \quad (25)$$

We obtain three independents from equation (23) to (25) which are highly nonlinear containing six unknowns$A, B, C, \beta, p and \rho$.

Now to obtain a definite solution.we use following physical conditions.

The shear scalar $\sigma^2$and scalar expansion $\theta$are proportional

$$B=C^m \quad (26)$$

Where $m$is non zero constant.i.e.$m\neq 0$

Subtracts equation (23) from (24) and applying equation (26), we get

$$\frac{\ddot{C}}{C}+(2m-1)\frac{\dot{C}^2}{C^2}=\frac{\alpha^2}{mC^{2m}} \quad (27)$$

We take $g(C)=\dot{C}$

From equation (27), we obtain

$$\frac{dg^2}{dC}+\frac{2(2m-1)g^2}{C}=\frac{2\alpha^2}{mC^{2m-1}} \quad (28)$$

Which is linear differential equation in $g^2(C)$

We obtain the solution as

$$C=m\left(\left[\frac{\alpha+mc}{m}\right]t+k_2\right)^{1/m} \quad (29)$$

$$B=m\left(\left[\frac{\alpha+mc}{m}\right]t+k_2\right) \quad (30)$$

$$A=m\left(\left[\frac{\alpha+mc}{m}\right]t+k_2\right) \quad (31)$$

Then metric equation (15) reduce to

$$ds^2=dt^2-m^2\left(\left[\frac{\alpha+mc}{m}\right]t+k_2\right)^2\left[dx^2+e^{-2\alpha x}dy^2+(k_1t+k_2)^{\frac{2(1-m)}{m}}dz^2\right] \quad (32)$$

Physical and Kinematical properties of the model

The spatial volume$V$ and the scale factor a are given by

$$V = m^3\left(\left[\frac{a+mc}{m}\right]t + k_2\right)^{\frac{2m+1}{m}} e^{-ax} \tag{33}$$

$$a = m\left(\left[\frac{a+mc}{m}\right]t + k_2\right)^{\frac{2m+1}{3m}} e^{\frac{-ax}{3}} \tag{34}$$

The generalized Hubble parameter H and the scalar expansion θ

$$H = \frac{(2m+1)}{3m}\left(\frac{a+mc}{m\left(\left[\frac{a+mc}{m}\right]t+k_2\right)}\right) \tag{35}$$

$$\theta = \frac{(2m+1)}{m}\left(\frac{a+mc}{m\left(\left[\frac{a+mc}{m}\right]t+k_2\right)}\right) \tag{36}$$

The shear scalar σ^2

$$\sigma^2 = \frac{(m-1)^2}{3m^2}\left(\frac{(a+mc)^2}{m^2\left(\left[\frac{a+mc}{m}\right]t+k_2\right)^2}\right) \tag{37}$$

The mean anisotropy parameter

$$A_m = \frac{2(m-1)^2}{(2m+1)^2} \tag{38}$$

The deceleration parameter

$$q = \frac{(m-1)}{(2m+1)} \tag{39}$$

Subtract equation (23-24) by applying equation (22), we get displacement vector field are given by

$$\frac{3}{4}\beta^2 = \frac{-(m+1)^2}{3m^2}\left(\frac{(a+mc)^2}{m^2\left(\left[\frac{a+mc}{m}\right]t+k_2\right)^2}\right) \tag{40}$$

We obtain energy density of the matter

$$\frac{1}{\left(\left[\frac{a+mc}{m}\right]t+k_2\right)^2}\left[\frac{(m^2-1)(a+mc)^2-m^2a^2}{m^4}\right] = \rho \tag{41}$$

Total pressure and proper pressure given as

$$\frac{\omega}{\left(\left[\frac{a+mc}{m}\right]t+k_2\right)^2}\left[\frac{m^2a^2-(m^2-2m-1)(a+mc)^2}{m^4}\right] = \bar{p} \tag{42}$$

$$\frac{\omega}{\left(\left[\frac{a+mc}{m}\right]t+k_2\right)^2}\left[\frac{m^2a^2-(m^2-2m-1)(a+mc)^2}{m^4}\right] + 3\xi H = p \tag{43}$$

The function of Ricci scalar and $f(\tilde{R},T)$ gravity is given by

$$\tilde{R} = \frac{1}{\left(\left[\frac{a+mc}{m}\right]t+k_2\right)^2}\left[\frac{(2m^2-4m-2)(a+mc)^2-m^2a^2}{m^4}\right] \tag{44}$$

$$\frac{1}{\lambda}f(\tilde{R},T) = \frac{1}{\left(\left[\frac{a+mc}{m}\right]t+k_2\right)^2}\left[\frac{(6m^2-10m-6)(a+mc)^2-4m^2a^2}{m^4}\right] \tag{45}$$

Summary and Conclusion

In this paper, we have studied Bianchi type-III cosmological model with $f(R,T)$ gravity in the presence of electromagnetic field based on Lyra geometry. To solve the field equations, we use shear scalar $\sigma^2$and scalar expansion θ are proportional and obtained

$B = C^m$ where m is arbitrary constant and B and C are metric coefficients.
It is observed that Generalized Hubble Parameter H, scalar expansion θ, and shear scalar σ^2 decrease with passage of time. the parameters H, θ, σ^2 are all infinite at $t = 0$.For $m = 0$ decelerating parameter $q = -1$ this indicates that universe is in accelerating phase. From the equation of spatial volume it is observed that the universe expands uniformly with increase of time. Model is isotropic for $m = 1$ otherwise it is anisotropic.

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