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Anisotropic Cosmological Model Bianchi Type-VI with Viscous Fluid Containing a Varying Λ

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Abstract: This paper explores the anisotropic nature of the Cosmological Model Bianchi Type -VI with Viscous Fluid in the presence of cosmological constant Λ. Cosmological Model Bianchi Type -VI helps in understanding anisotropic behaviour in the early universe and its implications. To find an exact solution for this model, a supplementary condition between the metric potential is used. Also, it is used the coefficient of shear viscosity is proportional to the scale of expansion, i.e., $\eta \propto \theta$. In this study, I assumed that the viscosity coefficient of a bulk viscosity fluid is a simple power function of energy density, $\xi(t) = \xi_0 \rho^r$ and it is solved for $r = 0$ and $r = 1$. The behaviour of cosmological parameters like pressure, energy density will be analysed, and it is also found that the cosmological constant Λ it is positive and it is decreasing with respect to time. Lastly, some physical aspects of the models are studied.
Keywords: Anisotropic, Bianchi Type-VI, Cosmological model, cosmological constant, Viscous Fluid.

I. INTRODUCTION

Cosmology is the branch of science devoted to studying the universe as a whole. The universe itself is a vast collection of galaxies, and its expansion and acceleration are described through cosmological models. Observations in modern astrophysics over the past decades reveal that the universe has been continuously expanding and accelerating since the Big Bang, evolving from an initial state of extremely high density and temperature. This has been confirmed through various cosmological observations, such as measurements of type-Ia supernovae (SNeIa), the cosmic microwave background (CMB), and large-scale structure (LSS) surveys ([1], [2], [3], [4], [5]). To understand the dynamics of the early universe, it is essential to consider cosmological models that incorporate anisotropic behaviour. The conventional framework, based on the isotropic Robertson-Walker metric, cannot fully account for possible anisotropies in the early universe. In this context, Bianchi models particularly Types V and VI provide valuable tools for exploring departures from perfect isotropy in spatially homogeneous but anisotropic settings. Nevertheless, present-day observations suggest that the universe is homogeneous and isotropic on large scales, while also undergoing accelerated expansion [6]. It is well established that the exact solutions of the General Theory of Relativity for homogeneous spacetimes are represented by Bianchi types [7]. In most studies of relativistic cosmological models, the energy–momentum tensor of matter is typically assumed to be that of a perfect fluid. However, for a more realistic description, it is necessary to incorporate viscosity effects, which have already drawn considerable attention from researchers. In cosmology, viscous fluids serve as effective mechanisms for dissipating anisotropies and can give rise to non-singular or inflationary behaviour during the early universe.

Misner ([8], [9]) propoed that strong dissipation caused by neutrino viscosity could significantly reduce the anisotropies of black-body radiation. Banerjee, Ribeiro, and Santos later presented exact anisotropic viscous-fluid cosmological solutions within the framework of Bianchi Type VI_0 models [10]. This makes it particularly valuable to examine gravitational fields described by spacetimes of different Bianchi types. Considering dissipative processes due to viscosity, Belinski and Khalatnikov [11] investigated homogeneous Bianchi-type cosmological models. They demonstrated that while viscosity cannot eliminate the cosmological singularity, it introduces qualitatively new features in the behaviour of solutions near the singularity. A striking outcome of their work is the suggestion that, at the time of the Big Bang, matter could be generated by the gravitational field itself. In a related study, Patel and Koppar (1991) explored several Bianchi VI_0 cosmologies with viscous fluids, emphasizing models exhibiting nonzero expansion and shear [12]. Singh, T., & Chaubey, R. (2007). Bianchi Type-V universe with a viscous fluid and Λ-term[13], while Huang [14] investigated Bianchi type-I models with bulk viscosity also modelled as a power-law function of energy density in a stiff matter universe. An important extension to standard cosmology is the consideration of a time-dependent cosmological constant Λ, inspired by observational evidence such as the accelerated expansion inferred from Type Ia supernovae. Models incorporating a dynamic cosmological term, Λ(t), have gained considerable attention as they provide a natural approach to addressing the cosmological constant problem.

Substantial observational support indicates the presence of Einstein's cosmological constant Λ, which evolves slowly with time and space. Zeldovich [15] and Carroll et al. [16] have suggested that the accelerated expansion of the universe may be closely linked to the cosmological density expressed through the time-varying term Λ.

In the context of Bianchi Type V models, Pradhan and Yadav (2004) constructed viscous-fluid cosmologies with a time-decreasing Λ, consistent with modern observational evidence [17]. The cosmological constant problem and its implications for cosmology with a variable Λ have been addressed by several researchers, including Dolgov [18], Sahani and Starobinsky [19], Vishwakarma ([20], [21]) and Singh et al. [22]. Further, Baghel and Singh examined Bianchi Type V universes with bulk viscosity alongside time-varying Λ and gravitational constant G, obtaining physically viable solutions [23], while Bali, Singh, and Singh (2012) analysed Bianchi Type V viscous-fluid models with a decaying vacuum energy density [24]. Extending these studies, Sadeghi, Amani, and Tahmasbi (2013) explored Bianchi Type VI universes with viscous fluids in the presence of Λ, showing solutions that exhibit accelerated expansion and the crossing of the phantom divide in the equation of state [25]. Investigations within alternative geometrical frameworks, such as Lyra geometry and modified gravity theories, further highlight the role of viscosity and evolving cosmological parameters in anisotropic cosmological evolution. This has motivated continued interest in cosmological models with bulk viscous fluids. Recently, SP Kandalkar, PP Khade, SP Gawande [26] studied homogeneous bianchi type I cosmological model filled with viscous fluid with a varying Λ such that these universes are generally expanding, shearing, and non-rotating. The influence of bulk viscosity on cosmological dynamics has also been analyzed by several authors within the framework of general relativity, including Johri and Sudershan [27] and Zimdahl [28].

In recent studies, Bianchi Type VI models incorporating viscous fluids and a variable Λ have been shown to yield accelerating solutions along with phantom-like transitions in the equation of state parameter. Despite these advances, a thorough investigation of Bianchi Type VI universes that simultaneously include viscous matter and a dynamically evolving Λ remains limited. The present work seeks to fill this gap by formulating an anisotropic Bianchi Type VI cosmological model with a viscous fluid and a time-dependent cosmological term. Our objective is to obtain exact solutions and to examine their physical as well as kinematical properties. Some physical aspects of the model are also studied. Section II, Metric and field equations. Section III, solutions of the field equation. Section IV, Model for power law expansion. section V, Evolution of cosmological parameters and lastly Section VI is the conclusion of overall solutions.

II. METRIC AND FIELD EQUATIONS

I have considered the metric of the space time of Bianchi type-VI as

$$ds^2 = -dt^2 + A^2dx^2 + B^2e^{-2qx}dy^2 + C^2e^{2qx}dz^2 \tag{1}$$

where A, B, C are the functions of cosmic time t only and q is constant

The Einstein field equation (in gravitational units c = 1, G = 1) read as

$$R_i^j - \frac{1}{2}Rg_i^j = -8\pi T_i^j + \Lambda g_i^j \tag{2}$$

where R_i^j is the Ricci tensor, R is the Ricci scalar and T_i^j is energy momentum tensor of a viscous fluid. Where T_i^j has the form as,

$$T_i^j = (\rho + p')u_iu^j - p'\delta_i^j + \eta g^{j\beta}\left(u_{i;\beta} + u_{\beta;i} - u_iu^\alpha u_{\beta;\alpha} - u_\beta u^\alpha u_{i;\alpha}\right) \tag{3}$$

$$\text{where, } p' = p - \left(\xi - \frac{2}{3}\eta\right)u^i_{;i} \tag{4}$$

where ρ is the energy density, p is the pressure, η and ξ are the coefficients of shear and bulk viscosity, respectively, and u_i is the flow vector satisfying the relations

$$g^{ij}u^iu^j = -1 \tag{5}$$

The semicolon (;) indicates covariant differentiation. Here take comoving coordinates,

$$u^1 = u^2 = u^3 = 0, \qquad u^4 = 1 \tag{6}$$

The Einstein field equations (2) for the metric (1) as

$$\frac{\ddot{B}}{B} + \frac{\ddot{C}}{C} + \frac{\dot{B}\dot{C}}{BC} + \frac{q^2}{A^2} = -8\pi\left(-p' + 2\eta\frac{\dot{A}}{A}\right) + \Lambda \tag{7}$$

$$\frac{\ddot{A}}{A} + \frac{\ddot{C}}{C} + \frac{\dot{A}\dot{C}}{AC} - \frac{q^2}{A^2} = -8\pi\left(-p' + 2\eta\frac{\dot{B}}{B}\right) + \Lambda \tag{8}$$

$$\frac{\ddot{A}}{A} + \frac{\ddot{B}}{B} + \frac{\dot{A}\dot{B}}{AB} - \frac{q^2}{A^2} = -8\pi\left(-p' + 2\eta\frac{\dot{C}}{C}\right) + \Lambda \tag{9}$$

$$\frac{\dot{A}\dot{B}}{AB}+\frac{\dot{B}\dot{C}}{BC}+\frac{\dot{A}\dot{C}}{AC}-\frac{q^2}{A^2}=-8\pi(-\rho-2p')+\Lambda \tag{10}$$

$$\frac{\dot{B}}{B}-\frac{\dot{C}}{C}=0 \tag{11}$$

Here, the dot over a field variable represents the differentiation with respect to time t.
The directional Hubble parameters in the direction of the x, y and z-axis respectively are

$$H_1=\frac{\dot{A}}{A}, \qquad H_2=\frac{\dot{B}}{B} \ \ and \ \ H_3=\frac{\dot{C}}{C} \tag{12}$$

The average scale factor and spatial volume as

$$V=a^3=ABC \tag{13}$$

The average Hubble parameter, which expresses the volumetric expansion rate of the universe is given by

$$H=\frac{\dot{a}}{a}=\frac{1}{3}\left(\frac{\dot{A}}{A}+\frac{\dot{B}}{B}+\frac{\dot{C}}{c}\right) \tag{14}$$

The mean anisotropy parameter is given by

$$\Delta=\frac{1}{3}\sum_{i=1}^{3}\left(\frac{H_i-H}{H}\right)^2=\frac{1}{3}\left(\frac{H_1^2+H_2^2+H_3^2}{H^2}-3\right) \tag{15}$$

The expansion scalar θ and the shear scalar σ of the fluid are defined as

$$\theta=3H \text{ and } \sigma^2=\frac{3}{2}\Delta H^2 \tag{16}$$

III. SOLUTION OF THE FIELD EQUATION

The equations from (7) to (11) are five independent field equations with eight unknowns $A, B, C, p, \rho, \eta, \xi$ and Λ. So, to find a determinate solution we take three additional constraints.
Now from equation (11)

$$B=kC \tag{17}$$

where k is integrating constant
Now firstly assume that

$$A=B^n \tag{18}$$

Where n is real number
Secondly, assume that the coefficient of shear viscosity is proportional to the expansion scale.

$$\eta\propto\theta \tag{19}$$

By using equations (11) and (16), equation (19) leads to

$$\eta=l\left(\frac{\dot{A}}{A}+\frac{2\dot{B}}{B}\right) \tag{20}$$

where l is the proportionality constant.
Adding equations (8) and (9) and subtract (10).

$$\frac{2\ddot{A}}{A}+\frac{\ddot{B}}{B}+\frac{\ddot{C}}{C}-\frac{\dot{B}\dot{C}}{BC}-\frac{q^2}{A^2}=-16\pi\eta\left(\frac{\dot{B}}{B}+\frac{\dot{C}}{C}\right)-8\pi\rho+\Lambda \tag{21}$$

By using equations (11) and (20), equation (21) becomes,

$$\frac{2\ddot{A}}{A}+\frac{\ddot{B}}{B}+\frac{\ddot{C}}{C}-\frac{\dot{B}^2}{B^2}-\frac{q^2}{A^2}=-32\pi l\frac{\dot{B}}{B}\left(\frac{\dot{A}}{A}+\frac{2\dot{B}}{B}\right)-8\pi\rho+\Lambda \tag{22}$$

Using equations (4) and (20), equation (7) becomes,

$$\frac{\ddot{B}}{B}+\frac{\ddot{C}}{C}+\frac{\dot{B}^2}{B^2}+\frac{q^2}{A^2}+8\pi\left[\xi-\frac{2l}{3}\left(\frac{\dot{A}}{A}+\frac{2\dot{B}}{B}\right)+2l\frac{\dot{A}}{A}\right]\left(\frac{\dot{A}}{A}+\frac{2\dot{B}}{B}\right)-\Lambda=8\pi p \tag{23}$$

From equations (13), (17) and (18) will get,

$$A=(kV)^{\frac{n}{n+2}} \tag{24}$$

$$B=(kV)^{\frac{1}{n+2}} \tag{25}$$

$$C = k^{\frac{-(n+1)}{(n+2)}} V^{\frac{1}{n+2}} \tag{26}$$

From equations (24), (25) and (26), metric (1) becomes,

$$ds^2 = -dt^2 + (kV)^{\frac{2n}{n+2}} dx^2 + e^{-2qx}(kV)^{\frac{2}{n+2}} dy^2 + e^{2qx} k^{\frac{-2(n+1)}{(n+2)}} V^{\frac{2}{n+2}} dz^2 \tag{27}$$

IV. MODEL FOR POWER LAW EXPANSION

Here I adapting a volumetric expansion by a power law relation as,

$$V = t^m \tag{28}$$

Where m is a positive constant. The positive value of the exponent m aligns with observational evidence that anticipates the universe.

The metric potential (24), (25) and (26) becomes,

$$A = k^{\frac{n}{n+2}} t^{\frac{nm}{n+2}} \tag{29}$$

$$B = k^{\frac{1}{n+2}} t^{\frac{m}{n+2}} \tag{30}$$

$$C = k^{\frac{-(n+1)}{(n+2)}} t^{\frac{m}{n+2}} \tag{31}$$

From equations (29), (30) and (31) it is clear that metric potential tends toward zero as the time t approaches to zero.

By using equations (29), (30) and (31) metric (27) can be written as,

$$ds^2 = -dt^2 + k^{\frac{2n}{n+2}} t^{\frac{2nm}{n+2}} dx^2 + e^{-2qx} k^{\frac{2}{n+2}} t^{\frac{2m}{n+2}} dy^2 + e^{2qx} k^{\frac{-2(n+1)}{(n+2)}} t^{\frac{2m}{n+2}} dz^2 \tag{32}$$

V. EVOLUTION OF COSMOLOGICAL PARAMETERS

In this section, we will discuss some physical and geometrical parameters to validate the cosmological model (32). Such as the pressure, energy density, mean Hubble parameter, expansion scalar, coefficient of shear viscosity η, shear scalar and anisotropic parameter.

The directional Hubble parameters by using (12), (29), (30) and (31) are

$$H_1 = \frac{nm}{(n+2)t}, \qquad H_2 = H_3 = \frac{m}{(n+2)t} \tag{33}$$

The average Hubble parameter using (14) and (33) is given by

$$H = \frac{m}{3t} \tag{34}$$

The coefficient of shear viscosity using (20) as

$$\eta = \frac{lm}{t} \tag{35}$$

The mean anisotropy parameter using (15), (33) and (34) is given by

$$\Delta = \frac{2(n-1)^2}{(n+2)^2} \tag{36}$$

The expansion scalar θ and the shear scalar σ of the fluid using (16), (34) and (36) are as

$$\theta = \frac{m}{t} \text{ and } \sigma = \frac{m(n-1)}{\sqrt{3}(n+1)t} \tag{37}$$

For the model (32) by using equation (23) the pressure of the universe as

$$8\pi p = \frac{(3m^2 - 2mn - 4n)}{(n+2)^2 t^2} + \frac{32\pi l m^2 (n-1)}{3(n+2)t^2} + \frac{8\pi\xi m}{t} + \frac{q^2}{k^{\frac{2n}{(n+2)}} t^{\frac{2mn}{(n+2)}}} - \Lambda \tag{38}$$

Similarly, by using equation (22), the energy density of the universe as

$$8\pi\rho = \frac{2n^2 m(1-m) - [32\pi l(n+2) + 1]m^2 + 2m(3n+2)}{(n+2)^2 t^2} + \frac{q^2}{k^{\frac{2n}{(n+2)}} t^{\frac{2mn}{(n+2)}}} + \Lambda \tag{39}$$

So, to specify ξ assume that the fluid obeys an equation of state of the form.

$$p = \omega\rho \tag{40}$$

where ω $(0 \le \omega \le 1)$ is constant.

Here $\xi(t)$ can be solved for the cosmological parameter. Most of the time, bulk viscosity is assumed to be a simple power function of energy density (Maarten [41]; Zimdahl [42])

$$\xi(t) = \xi_0 \rho^r \tag{41}$$

where ξ_0 and r are constant.

If $r = 1$ equation (41) may correspond to a radiative fluid (Weinberg 1972). However, more realistic models are based on r lying in the region $0 \le r \le \frac{1}{2}$.

By using (41) equation (38) becomes,

$$8\pi p = \frac{(3m^2 - 2mn - 4n)}{(n+2)^2 t^2} + \frac{32\pi l m^2 (n-1)}{3(n+2)t^2} + \frac{8\pi \xi_0 \rho^r m}{t} + \frac{q^2}{k^{\frac{2n}{(n+2)}} t^{\frac{2mn}{(n+2)}}} - \Lambda \tag{42}$$

Model I: Solution for $\xi = \xi_0$

When $r = 0$ equation (41) can $\xi = \xi_0 = constant$. Hence in this case equation (38) with the use of (39) and (40), becomes

$$8\pi\rho(1+\omega) = \frac{3m^2 - 2mn - 4n + 2n^2 m(1-m) - [32\pi l(n+2) + 1]m^2 + 2m(3n+2)}{(n+2)^2 t^2} + \frac{32\pi l m^2 (n-1)}{3(n+2)t^2} + \frac{8\pi \xi_0 m}{t} + \frac{2q^2}{k^{\frac{2n}{(n+2)}} t^{\frac{2mn}{(n+2)}}} \tag{43}$$

To finding Λ, eliminate $\rho(t)$ between (39) and (43).

$$(1+\omega)\Lambda = \frac{3m^2 - 2mn - 4n - \omega[2n^2 m(1-m) - [32\pi l(n+2) + 1]m^2 + 2m(3n+2)]}{(n+2)^2 t^2} + \frac{32\pi l m^2 (n-1)}{3(n+2)t^2} + \frac{8\pi \xi_0 m}{t} + (1-\omega)\frac{q^2}{k^{\frac{2n}{(n+2)}} t^{\frac{2mn}{(n+2)}}} \tag{44}$$

Model II: Solution for $\xi = \xi_0 \rho$

When $r = 1$ equation (41) can $\xi = \xi_0 \rho$. Hence in this case equation (38) with the use of (39) and (40), becomes,

$$8\pi\rho\left(1 + \omega - \frac{\xi_0 m}{t}\right) = \frac{3m^2 - 2mn - 4n + 2n^2 m(1-m) - [32\pi l(n+2) + 1]m^2 + 2m(3n+2)}{(n+2)^2 t^2} + \frac{2q^2}{k^{\frac{2n}{(n+2)}} t^{\frac{2mn}{(n+2)}}} + \frac{32\pi l m^2 (n-1)}{3(n+2)t^2} \tag{45}$$

To finding Λ, eliminate $\rho(t)$ between (39) and (45).

$$\left(1 + \omega - \frac{\xi_0 m}{t}\right)\Lambda = \left[\frac{3m^2 - 2mn - 4n - \left(\omega - \frac{\xi_0 m}{t}\right)[2n^2 m(1-m) - (32\pi l(n+2) + 1)m^2 + 2m(3n+2)]}{(n+2)^2 t^2}\right] + \left[\frac{32\pi l m^2 (n-1)}{3(n+2)t^2} + \left(1 - \omega + \frac{\xi_0 m}{t}\right)\frac{q^2}{k^{\frac{2n}{(n+2)}} t^{\frac{2mn}{(n+2)}}}\right] \tag{46}$$

VI. CONCLUSION

I have studied the Bianchi type-VI an isotropic cosmological model in the presence of viscous fluid with varying cosmological constant Λ. My work aims to obtain solutions by using cosmological model Bianchi type-VI. Here I have assumed that the fluid obeys an equation of state of the form $p = \omega\rho$ and also assumed bulk viscosity is a simple power function of energy density which is given by $\xi(t) = \xi_0 \rho^r$. The models for the values $r = 0, 1$ are studied. From this study, I observed from equation (38) the pressure p continuously decreasing for late time and approaching to negative times cosmological constant Λ as $t \to \infty$. From equations (44) and (46), it is observed that the positive cosmological constant is a decreasing function of time and approaches to small value in the present epoch. From equations (43) and (45), it is observed that the energy density is a decreasing function of time and approaches to 0 as $t \to \infty$. From equation (37), it is observed that the scalar expansion factor θ is a decreasing function of 't' and approach to zero as t tends to infinity. Since $\lim_{t\to\infty} \frac{\sigma}{\theta} = constant$, the model is not isotropic for the future large value of t. From equation (32) it is shown that the given model starts with a big-bang at $t = 0$ and the expansion in the model increases as time increases. For this model the spatial volume $V \to \infty$ as $t \to \infty$.

The Anisotropic parameter of the expansion is found to be constant. The evolution of Hubble parameter (H) with respect to cosmic time (t) indicates that the value of Hubble parameter (H) is very high at the early time of universe and is decreases very rapidly at late time, and it is constant to zero when the time is increases.

Thus, I conclude that the cosmological constant in this model is decreasing function with respect to time and it approaches to small positive value as time increases. From all this, it is clear that the universe is experiencing accelerated expansion in the later phase of evolution.

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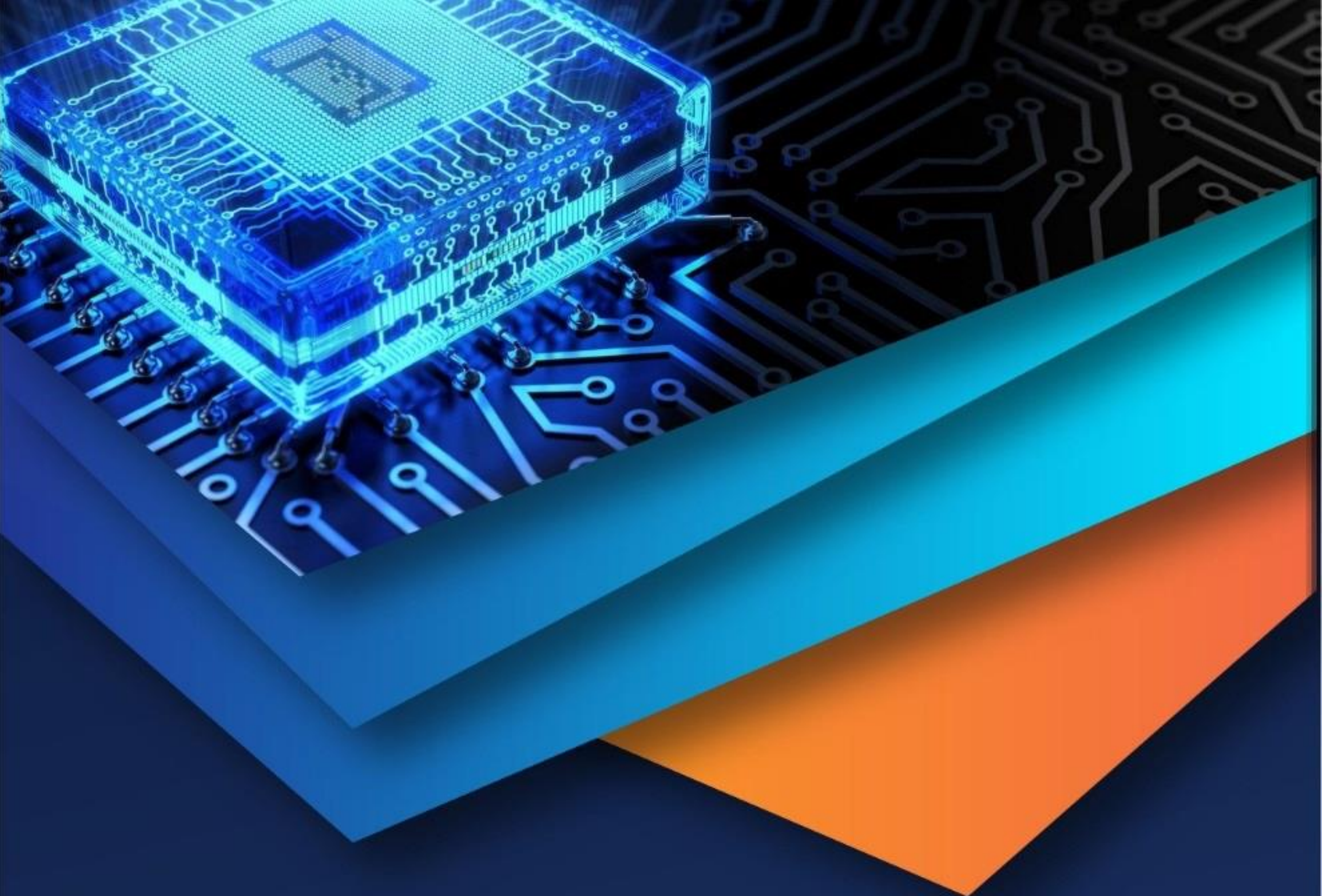

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