© 2019 IJSRSET | Volume 6 | Issue 1 | Print ISSN: 2395-1990 | Online ISSN : 2394-4099
Themed Section : Science and Technology
DOI : https://doi.org/10.32628/IJSRSET196149

Bianchi Type VI Cosmological Model with Dynamical Cosmological Parameters G and Λ in the presence of Bulk Viscous Stress

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ABSTRACT

In the present study, we have obtained Bianchi type VI anisotropic model of the universe filled with a bulk viscous stress in the presence of variable gravitational and cosmological constants. Here we have assumed the cosmological term in the form $\Lambda \propto H^{2}$ to discuss the effect of cosmological variables. It is found that the bulk viscosity coefficient (ξ) is a decreasing function of time. The expression for proper distance, luminosity distance, angular diameter distance, look back time and distance modulus curve have been analyzed and also the distance modulus curve of derived model nearly matches with Supernova Ia (SN Ia) observations.

Keywords : Bianchi Type VI, Bulk Viscous Stress, Gravitational and Cosmological Parameters

I. INTRODUCTION

Cosmology is one of the great estintellectual achievements of all time beginning from its origin. It is that branch of astronomy, which deals with the large scale structure of the universe. Using astronomical data, our resulting cosmological model of universe compare with the present day universe. Cosmic fluid is considered as perfect fluid in most treatments of cosmology. However, bulk viscosity is expected to play an important role at certain stages of an expanding universe. Nowadays viscosity mechanism has attracted the attention of many researchers. At early stages of evolution of the universe, when radiation is in the form of photons as well as neutrino decoupled, the matter behaved like a viscous fluid.

In recent years there has been considerable interest in the cosmological models with variable gravitational constant G and the cosmological constant Λ. Variation of gravitational constant was first suggested by Dirac [1] in an attempt to understand the appearance of certain very large numbers, when atomic and cosmic world are compared. He postulates that the gravitational constant G decreases inversely with cosmic time. Beesham [2] has studied the creation with variable G and pointed out the variation of the form $G \sim t^{-1}$ originally proposed by Dirac [1].

On the other hand, in 1917 Einstein introduced the cosmological constant Λ to account for a stable static universe as appeared to him at that time. It is believed that the cosmological constant was very large in the early universe, relaxed to its present small value in the course of expansion of the universe by creating massive or massless particles. Cosmological constant problem arises because of large discrepancy between the observational value of Λ and the theoretical value. Many solutions convening to this problem were proposed by considering dynamical Λ [3]-[10]. It is found that the presence of a non-zero cosmological constant is one of the most important reason for the acceleration [11, 12]. Discussion on cosmology with a time varying cosmological constant is presented by several authors. Samdurkar and Sen [13] investigated the effect of bulk viscosity on Bianchi Type V cosmological models with varying Λ in general relativity. Dwivedi analyzed that Bulk viscous Bianchi type –V cosmological models with stiff fluid and time dependent cosmological term [14]. Some Bianchi type VI viscous fluid cosmological models were investigated by Patel and Kopper [15]. Dunn and Tupper [16] studied a class of Bianchi type VI cosmological models with electromagnetic field. Arbab [17] investigated the cosmological models with variable cosmological and gravitational constants and bulk viscous fluid. A new class of LRS Bianchi type VI0 universe with free gravitational field and Decaying vacuum energy density were proposed by Pradhan et.al. [18]. A number of authors [19]-[30] have studied the variation of G and Λ within the framework of general relativity in different context.

Eckart [31] has made the first attempt to develop the relativistic theory of nonequilibrium thermodynamics to study the effect of bulk viscosity. But Eckart theory has several drawbacks including violation of causality and stability. Readers interested in the general theory of causal thermodynamics are urged to consult the excellent survey report of Maartens [32] and Zimdahl [33] and references cited therein.

With the above motivations, in this paper we have studied Bianchi type VI cosmological model filled variable G and Λ in the presence of bulk viscous stress in the framework of general relativity. We have also obtained bulk viscosity coefficient in Eckart, Truncated and FIS causal theory. The expression for proper distance, luminosity distance, angular diameter distance, look back time and distance modulus curve have been analyzed and also the distance modulus curve of derived model nearly matches with Supernova Ia (SN Ia) observations.

II. METRIC AND FIELD EQUATIONS

It is well-known that the energy-momentum tensor T_{ij} in the form of bulk viscous stress may be considered as

$$T_{ij} = (\rho + p + \Pi)u_{ij} - (p + \Pi)g_{ij} \tag{1}$$

Here ρ, p and Π represents energy density, perfect fluid pressure and bulk viscous stress respectively and u^i is the four velocity vector.

Here we consider the spatially homogeneous and anisotropic Bianchi type VI space time in the form

$$ds^2 = -dt^2 + A_1^2 dx^2 + A_2^2 e^{-2\alpha x} dy^2 + A_3^2 e^{2\alpha x} dz^2 \tag{2}$$

where A_1, A_2 and A_3 are functions of the cosmic time t and α is a constant.

The Einstein field equations are

$$R_{ij} - \frac{1}{2} R g_{ij} = -8\pi G T_{ij} + \Lambda g_{ij} \tag{3}$$

Here R_{ij} is the Ricci tensor, R is the Ricci scalar curvature, T_{ij} is the energy–momentum tensor of matter.

In co-moving coordinate system u_i= (0, 0, 0, 1), the Einstein's field equation together with (1) for the metric (2) yields

$$\frac{\ddot{A}_2}{A_2} + \frac{\ddot{A}_3}{A_3} + \frac{\dot{A}_2\dot{A}_3}{A_2A_3} + \frac{\alpha^2}{A_1^2} = -8\pi G (p + \Pi) + \Lambda \tag{4}$$

$$\frac{\ddot{A}_1}{A_1} + \frac{\ddot{A}_3}{A_3} + \frac{\dot{A}_1\dot{A}_3}{A_1A_3} - \frac{\alpha^2}{A_1^2} = -8\pi G (p + \Pi) + \Lambda \tag{5}$$

$$\frac{\ddot{A}_1}{A_1} + \frac{\ddot{A}_2}{A_2} + \frac{\dot{A}_1\dot{A}_2}{A_1A_2} - \frac{\alpha^2}{A_1^2} = -8\pi G (p + \Pi) + \Lambda \tag{6}$$

$$\frac{\dot{A}_1\dot{A}_2}{A_1A_2} + \frac{\dot{A}_1\dot{A}_3}{A_1A_3} + \frac{\dot{A}_2\dot{A}_3}{A_2A_3} - \frac{\alpha^2}{A_1^2} = 8\pi G \rho + \Lambda \tag{7}$$

$$\frac{\dot{A}_2}{A_2} - \frac{\dot{A}_3}{A_3} = 0 \tag{8}$$

where a dot denotes ordinary differentiation with respect to t.

The average scale factor R and volume V are given by

$$R^3 = V = A_1A_2A_3 \tag{9}$$

The energy conservation equation is

$$\dot\rho + 3(\rho + p + \Pi)H + \rho\frac{\dot G}{G} + \frac{\dot\Lambda}{8\pi G} = 0 \tag{10}$$

which splits into

$$\dot\rho + 3(\rho + p + \Pi)H = 0 \tag{11}$$

and

$$8\pi\dot G\rho + \dot\Lambda = 0 \tag{12}$$

The generalized mean Hubble parameter H is defined by

$$H = \frac{\dot R}{R} = \frac{1}{3}(H_1 + H_2 + H_3) \tag{13}$$

where the directional Hubble parameters H_1, H_2 and H_3 are given by

$$H_1 = \frac{\dot A_1}{A_1}, H_2 = \frac{\dot A_2}{A}, H_3 = \frac{\dot A_3}{A} \tag{14}$$

The scalar expansion and shear scalar are given by

$$\theta = \frac{\dot A_1}{A_1} + \frac{\dot A_2}{A} + \frac{\dot A_3}{A} \tag{15}$$

$$2\sigma^2 = \sum_{i=1}^{3} H_i^2 - \frac{\theta^2}{3} \tag{16}$$

The deceleration parameter q is defined by

$$q = -\frac{R\ddot R}{\dot R^2} \tag{17}$$

The sign of q indicates whether the model inflates or not. A positive sign of q corresponds to the standard decelerating model whereas the negative sign of q indicates inflation. The recent observations of SNIa (Reiss et.al. [34], Perlmutter et.al.[35]) reveal that the present universe is accelerating and the value of DP lies somewhere in the range -1<q<0.

III. SOLUTION OF FIELD EQUATIONS

From Eqn. (8), we get

$$A_2 = A_3 \tag{18}$$

Using (18), Eqn. (4)-(7) reduces to

$$\frac{2\ddot A_2}{A_2} + \frac{\dot A_2^2}{A_2^2} + \frac{\alpha^2}{A_1^2} = -8\pi G(p + \Pi) + \Lambda \tag{19}$$

$$\frac{\ddot A_1}{A_1} + \frac{\ddot A_2}{A_2} + \frac{\dot A_1\dot A_2}{A_1A_2} - \frac{\alpha^2}{A_1^2} = -8\pi G(p + \Pi) + \Lambda \tag{20}$$

$$\frac{2\dot A_1\dot A_2}{A_1A_2} + \frac{\dot A_2^2}{A_2^2} - \frac{\alpha^2}{A_1^2} = 8\pi G\rho + \Lambda \tag{21}$$

Here we assume the cosmological term as a function of Hubble parameter H in the following form (Arbab [36])

$$\Lambda = 3\beta H^2 \tag{22}$$

In order to solve the above Eqns., we use the physical condition that expansion scalar is proportional to shear scalar, which leads to

$$A_1 = A_2^n \quad \text{where } n>1 \tag{23}$$

Combining Eqn. (9), (18) and (23), we have

$$A_1 = V^{\frac{n}{n+2}} \tag{24}$$

and

$$A_2 = V^{\frac{1}{n+2}} \tag{25}$$

Equating Eqn. (19) and (20),

$$\frac{\ddot A_2}{A_2} - \frac{\ddot A_1}{A_1^2} + \frac{\dot A_2^2}{A_2^2} - \frac{\dot A_1\dot A_2}{A_1A_2} + \frac{2\alpha^2}{A_1^2} = 0 \tag{26}$$

Substituting Eqn. (24) and (25) in (26), we get

$$\frac{\ddot V}{V} = \frac{2\alpha^2(n+2)}{(n-1)}\frac{1}{V^{\frac{2n}{n+2}}} \tag{27}$$

after the first integral of Eqn. (27) , we obtain

$$\int\frac{dV}{\sqrt{V^{\frac{4}{n+2}} + K_0}} = \frac{\alpha(n+2)}{\sqrt{n-1}}t \tag{28}$$

where K_0 is an arbitrary constant.

It is clear that Eqn. (28)is not possible to solve in general, so in order to solve the problem completely we have to choose $K_0 = 0$ so that (28) be integrable.

Hence the solution of Eqn. (28) is

$$V = \left(\frac{n\alpha}{\sqrt{n-1}}\right)^{\frac{n+2}{n}}(t+m)^{\frac{n+2}{n}} \tag{29}$$

Hence we have

$$A_1 = \left(\frac{n\alpha}{\sqrt{n-1}}\right)(t+m) \quad (30)$$

and

$$A_2 = \left(\frac{n\alpha}{\sqrt{n-1}}\right)^{\frac{1}{n}}(t+m)^{\frac{1}{n}} \quad (31)$$

with these scale factors, the metric (2) can be written as

$$ds^2 = -dt^2 + \left(\frac{n\alpha}{\sqrt{n-1}}\right)^2 (t+m)^2 dx^2 + \left(\frac{n\alpha}{\sqrt{n-1}}\right)^{\frac{2}{n}} (t+m)^{\frac{2}{n}} \left(e^{-2\alpha x} dy^2 + e^{2\alpha x} dz^2\right) \quad (32)$$

with the help of Eqn. (30) and (31), Hubble parameter (H), expansion scalar (θ), shear scalar (σ) and deceleration parameter (q) can be obtained as

$$H = \left(\frac{n+2}{3n}\right)\frac{1}{(t+m)} \quad (33)$$

$$\theta = 3H = \frac{(n+2)}{n}\frac{1}{(t+m)} \quad (34)$$

$$\sigma = \frac{(n-1)}{n\sqrt{3}}\frac{1}{(t+m)} \quad (35)$$

$$q = \frac{2(n-1)}{(n+2)} \quad (36)$$

From Eqn. (21), we get

$$8\pi G\rho = \left[\frac{(n+2)\{3-\beta(n+2)\}}{3n^2}\right]\frac{1}{(t+m)^2} \quad (37)$$

where $3-(n+2)\beta > 0$

and Eqn. (12) becomes

$$8\pi \dot{G}\rho = \frac{2\beta(n+2)^2}{3n^2}\frac{1}{(t+m)^3} \quad (38)$$

From Eqn. (37) and (38), we get

$$\frac{\dot{G}}{G} = \frac{2\beta(n+2)}{\{3-\beta(n+2)\}}\frac{1}{(t+m)} \quad (39)$$

Integrating the above Eqn. one can obtain

$$G = M_0 (t+m)^{\frac{2\beta(n+2)}{3-\beta(n+2)}} \quad (40)$$

where M_0 is an integrating constant.

Substituting Eqn. (40) in Eqn. (37), it gives

$$\rho = \frac{(n+2)\{3-\beta(n+2)\}}{24\pi n^2 M_0}\frac{1}{(t+m)^{\frac{6}{3-\beta(n+2)}}} \quad (41)$$

The energy density should be positive for the condition $\beta < \frac{3}{n+2}$. Also it can be easily seen that the energy density is always a decreasing function during evolution of the universe.

By assuming EOS $p = \gamma\rho$, we write

$$p = \frac{\gamma(n+2)\{3-\beta(n+2)\}}{24\pi n^2 M_0}\frac{1}{(t+m)^{\frac{6}{3-\beta(n+2)}}} \quad (42)$$

Hence from (19), we have

$$\Pi = \frac{\beta(n+2)^2 + 3(n-2) - \gamma(n+2)\{3-\beta(n+2)\}}{24\pi n^2 M_0}\frac{1}{(t+m)^{\frac{6}{3-\beta(n+2)}}} \quad (43)$$

In (Extended irreversible thermodynamics (EIT), the bulk viscous stress Π satisfies a transport equation given by

$$\Pi + \tau\Pi_4 = -3\xi H - \frac{\varepsilon}{2}\tau\Pi\left[3H + \frac{\tau_4}{\tau} - \frac{\xi_4}{\xi} - \frac{T_4}{T}\right] \quad (44)$$

where τ relaxation time and T is temperature. The parameter ε takes the value 0 or 1. Here $\varepsilon = 0$ represents truncated Israel-Stewart theory, $\varepsilon = 1$ represents full Isreal-Stewart causal theory and $\tau = 0$ recovers the non-causal Eckart theory.

The Gibb's integrability condition [Maarten (1995)] is defined as

$$T = \exp\left(\int \frac{dp(\rho)}{\rho + p(\rho)}\right) \quad (45)$$

Using EOS, (45) reduces to

$$T = T_0 \rho^{\frac{\gamma}{\gamma+1}} \quad (46)$$

where T_0 is a constant.

Using (41) in (45), the temperature (T) is as follows

$$T = T_0\left(\frac{(n+2)\{3-\beta(n+2)\}}{24\pi n^2 M_0}\right)^{\frac{\gamma}{1+\gamma}}\frac{1}{(t+m)^{\frac{6\gamma}{(1+\gamma)\{3-\beta(n+2)\}}}} \quad (47)$$

It is been observed that the density (ρ), the cosmological constant (Λ) and the temperature (T) are decreasing function of time which can be seen in Fig. 1, Fig. 2 and Fig. 3 whereas the gravitational constant (G) is increasing function of time which is shown in Fig. 4.

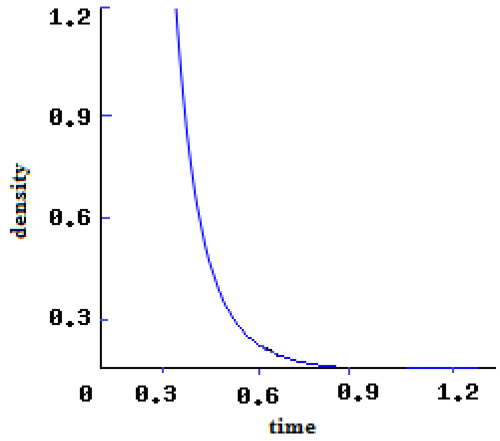

Fig. 1: density vs. time

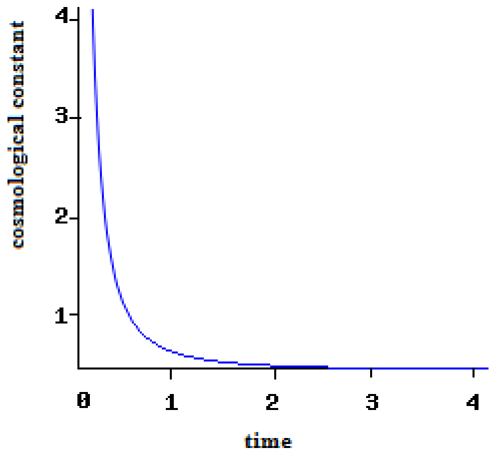

Fig. 2:cosmological constant vs. time

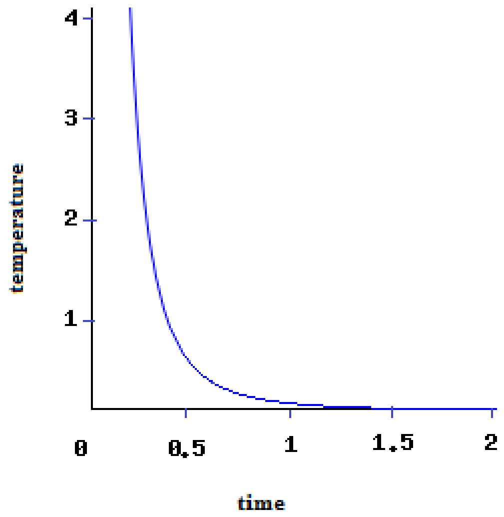

Fig. 3: temperature vs. time

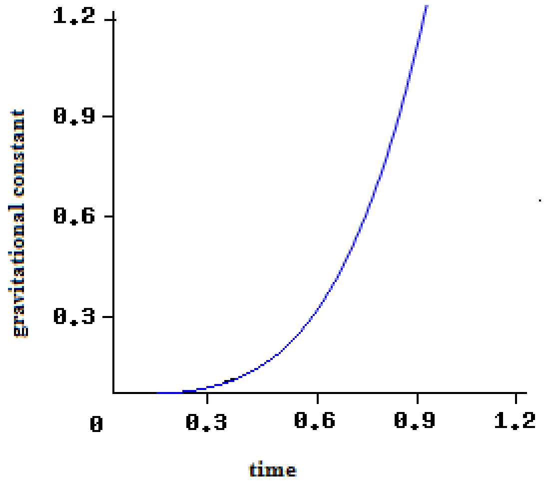

Fig. 4: gravitational constant vs. time

Bulk Viscosity in Eckart's Theory:

The evolution Eqn. (44) for bulk viscosity in non-causal Eckart's theory reduces to

$$\Pi = -3\xi H \tag{48}$$

with the help of (33) and (43), we get bulk viscosity coefficient as

$$\xi = -\frac{\Pi}{3H}$$

$$= \frac{\gamma(n+2)\{3-\beta(n+2)\}-\beta(n+2)^2-3(n-2)}{24\pi n^2 M_0}\frac{1}{(t+m)^{\frac{3+\beta(n+2)}{3-\beta(n+2)}}} \tag{49}$$

Bulk Viscosity in Truncated Theory:

In truncated theory (i.e. $\varepsilon = 0$), the evolution Eqn. (44) for bulk viscosity reduces to

$$\Pi + \tau \Pi_4 = -3\xi H \tag{50}$$

The relation between τ and coefficient of bulk viscosity ξ is given by

$$\tau = \frac{\xi}{\rho} \qquad (51)$$

Thus the Eqn. (50) reduces to

$$\Pi + \frac{\xi}{\rho}\Pi_4 = -3\xi H \qquad (52)$$

Using Eqns. (33), (41) and (43), we obtain

$$\xi = \frac{(n+2)\{3-\beta(n+2)\}^2 \beta_0}{24\pi\, n\, M_0\left(6n\beta_0 - (n+2)^2\{3-\beta(n+2)\}^2\right)} \frac{1}{(t+m)^{\frac{3+\beta(n+2)}{3-\beta(n+2)}}} \qquad (53)$$

Bulk Viscosity in FIS Causal Theory:

In FIS theory (i.e. $\varepsilon = 1$), the evolution Eqn. (44) for bulk viscosity reduces to

$$\Pi + \tau\,\Pi_4 = -3\xi\, H - \frac{1}{2}\tau\,\Pi\left[3H + \frac{\tau_4}{\tau} - \frac{\xi_4}{\xi} - \frac{T_4}{T}\right]$$

Thus we obtain

$$\xi = \frac{(n+2)(3-\beta(n+2))^2(1+\gamma)\beta_0}{24\pi\, n\, M_0\left(3n\beta_0 - (n+2)(1+\gamma)(3-\beta(n+2))(\beta_0+n+2)\right)} \frac{1}{(t+m)^{\frac{3+\beta(n+2)}{3-\beta(n+2)}}} \qquad (54)$$

To investigate the consistency of the model (32), we measure the physical parameters such as proper distance, luminosity distance, angular diameter etc.

Proper Distance

The proper distance $d(z)$ is defined as the distance between a cosmic source emitting light at any instant $t = t_1$ located at $r = r_1$ with redshift z and an observer at $r = 0$ and $t = t_0$ receiving the light from the source emitted i.e.

$$d(z) = R_0 r_1 \qquad (55)$$

where $r_1 = \int_{t_1}^{t_0} \frac{dt}{R(t)}$

Hence

$$d(z) = \frac{(n+2)}{2(n-1)} \frac{\left((1+z)^{\frac{2n-2}{n+2}} - 1\right)}{H_0(1+z)^{\frac{2n-2}{n+2}}} \qquad (56)$$

where $1+z = \frac{R_0}{R}$ = redshift and R_0 is the present scale factor of the universe.

Luminosity Distance

Luminosity distance is the important concept of theoretical cosmology of a light source. The luminosity distance is a way of expanding the amount of light received from a distant object. It is defined in such a way as generalizes the inverse-square law of the brightness in the static Euclidean space to an expanding curved space.

The luminosity distance of a light source is defined as

$$d_L^2 = \frac{L}{4\pi\, l} \qquad (57)$$

where L is the absolute luminosity and l is the apparent luminosity of source. Therefore one can write

$$d_L = (1+z)d(z) \qquad (58)$$

Using (56), Eqn. (58) reduces to

$$H_0 d_L = \frac{(n+2)}{2(n-1)} \frac{\left((1+z)^{\frac{2n-2}{n+2}} - 1\right)}{(1+z)^{\frac{n-4}{n+2}}} \qquad (59)$$

Angular Diameter Distance

The angular diameter distance is a measure of how large objects appear to be. As with the luminosity distance, it is defined as the distance that an object of known physical extent appears to be at, under the assumption of the Euclidean geometry.

The angular diameter d_A of a light source of proper distance is given by

$$d_A = (1+z)^{-2} d_L \qquad (60)$$

Using (59), we get

$$d_A = H_0^{-1} \frac{(n+2)}{2(n-1)} \frac{\left((1+z)^{\frac{2n-2}{n+2}} - 1\right)}{(1+z)^{\frac{3n}{n+2}}} \qquad (61)$$

Look back Time

The look back time is defined as the elapsed time between the present age of universe t_0 and the time t when the light from a cosmic source at a particular redshift z was emitted.

In the context of our model it is given by

$$t_0 - t = \int_R^{R_0} \frac{dR}{\dot{R}} \tag{62}$$

which on simplification gives

$$H_0(t_0 - t) = \frac{n+2}{3n}\left(1-(1+z)^{-\frac{3n}{n+2}}\right) \tag{63}$$

Distance Modulus Curve

The distance modulus is given by

$$\mu = 5\log d_L + 25, \tag{64}$$

Using (59), we obtain the expression for distance modulus (μ) in terms of red shift parameter (z) as

$$\mu = 5\log\left(\frac{(n+2)}{2(n-1)H_0}\frac{\left((1+z)^{\frac{2n-2}{n+2}}-1\right)}{(1+z)^{\frac{n-4}{n+2}}}\right)+25 \tag{65}$$

The observed value of distance modulus $\mu(z)$ at different redshift parameters (z) given in the Table below

Table

Redshift (z)	Supernovae Ia (μ)	Our model (μ)
0.014	33.73	32.72
0.026	35.62	34.07
0.036	36.39	34.79
0.040	36.38	35.02
0.050	37.08	35.51
0.063	37.67	36.01
0.079	37.94	36.51
0.088	38.07	36.75
0.101	38.73	37.06
0.160	39.08	38.08
0.240	40.68	39.00
0.380	42.02	40.05
0.430	42.33	40.34
0.480	42.37	40.59
0.620	43.11	41.19
0.740	43.35	41.61
0.778	43.81	41.73
0.828	43.59	41.88
0.886	43.91	42.04
0.910	44.44	42.10
1.056	44.25	42.46

The observe value of distance modulus at different redshift parameters are employed to draw the curve corresponding to the calculate value of $\mu(z)$. The plot of observed $\mu(z)$ (dotted line) and calculated $\mu(z)$ (solid line) versus redshift parameter (z) showed in Fig. 5.

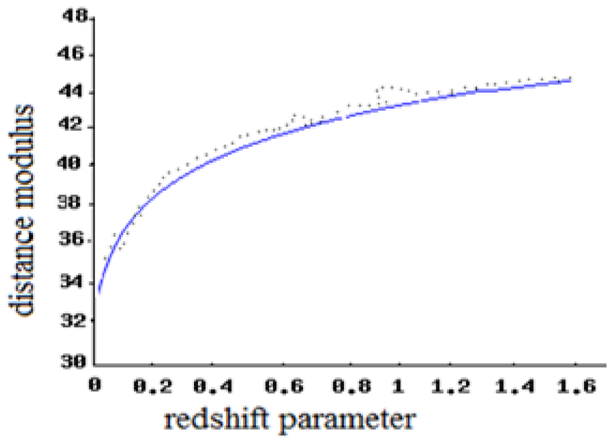

Fig. 5: distance modulus vs. redshift parameter

IV. CONCLUSION

In this paper, we have investigated exact solution of Einstein's field equations for a Bianchi type VI cosmological model filled variable G and Λ in the presence of bulk viscous stress under the assumption that the cosmological term is a function of Hubble parameter (H) and expansion scalar is proportional to shear scalar. In this paper, the form of cosmological term Λ is physically reasonable as observations suggest that Λ is very small in the present universe. It can also be observed that scalar expansion (θ), Hubble parameter (H) and shear scalar (σ) decreases with increase of time. The bulk viscosity coefficient (ξ) decrease as time increases. From (41) and (42), we can see that energy density and pressure will vanish with the increase of cosmic time. Hence they represent vacuum cosmological models in general relativity for large values of t also the bulk viscosity coefficient (ξ) decrease as time increases. We find $\frac{\sigma}{\theta}$ = constant, which shows that the anisotropy in the universe is maintained throughout. However it becomes isotropic for $n = 1$. We have also taken an account of the consistency of our model with observational parameters such as proper distance, luminosity distance, angular diameter distance, look back time. Also we compared the observe value of distance modulus with the calculated value of derived model (Fig.5 and Table).

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Cite this article as :
Shilpa Samdurkar, Seema Bawnerkar, "Bianchi Type VI Cosmological Model with Dynamical Cosmological Parameters G and Λ in the presence of Bulk Viscous stress", International Journal of Scientific Research in Science, Engineering and Technology (IJSRSET), ISSN : 2456-3307, Volume 6 Issue 1, pp. 246-254, January-February 2019. Available at doi : https://doi.org/10.32628/IJSRSET196149
Journal URL : http://ijsrset.com/IJSRSET196149