

# HIGHER DIMENSIONAL COSMOLOGICAL MODEL OF THE UNIVERSE WITH VARIABLE EQUATION OF STATE PARAMETER IN THE PRESENCE OF $G$ AND $\Lambda$

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In this paper we have obtained the exact solution of the Einstein field equations by using global equation of state of the form  $p = \frac{1}{3}\rho\phi$ , where  $\phi$  is a function of the scale factor  $R$  for Zeldovich fluid satisfying  $G = G_0(\frac{R}{R_0})^m$ . We also studied the two variable  $\Lambda$  model, viz.  $\Lambda \sim (\frac{\dot{R}}{R})^2$  and  $\Lambda \sim \rho$  under the assumption that the equation of state parameter  $\omega$  is time-dependent i.e.  $\omega = \omega(t)$  in the framework of Kaluza-Klein theory of gravitation.

*Key words:* gravitational constants, cosmological constants, Zeldovich fluid, higher dimension,  $\Lambda$ -model, variable  $G$  and  $\omega$ .

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## 1. INTRODUCTION

Kaluza-Klein theory has a long and venerable history. However, the original Kaluza version of this theory suffered from the assumption that the 5-dimensional metric does not depend on the extra coordinate (the cylinder condition). Hence the proliferation in recent years of various versions of Kaluza-Klein theory, supergravity and superstrings. In the last years number of authors (Wesson (1992), Chatterjee et al. (1994a), Chatterjee (1994b), Chakraborty and Roy (1999)) have considered multi dimensional cosmological model. Kaluza-Klein achievements is shown that five dimensional general relativity contains both Einstein's four-dimensional theory of gravity and Maxwell's theory of electromagnetism.

Chatterjee and Banerjee (1993) and Banerjee et al. (1995) have studied Kaluza-Klein inhomogeneous cosmological model with and without cosmological constants respectively. So far there has been many cosmological solution dealing with higher dimensional model containing a variety of matter field. However, there is a few work in a literature where variable  $G$  and  $\Lambda$  have been consider in higher dimension.

Beesham (1986a, 1986b) and Abdel-Rahman (1990) used a theory of gravitation using  $G$  and  $\Lambda$  as no constant coupling scalars. Its motivation was to include a  $G$ -coupling 'constant' of gravity as pioneered by Dirac (1937). Since the similar papers by Dirac (1938), a possible variation of  $G$  has been investigated with no success by several teams, through geophysical and astronomical observations, at the scale of solar system and with binary systems (Uzan (2003)). However, it should be stressed that we are talking here about time variations at a cosmological scale and cosmological observations still can not put strong limits on such a variation, specially at the late times of the evolution. In any case the strongest constraints are the presently observed  $G_0$  value and observational limits of  $\Lambda_0$ . Sistero (1991) found exact solution for zero pressure models satisfying  $G = G_0(\frac{R}{R_0})^m$ . Barrow (1996) formulated and studied the problem of varying  $G$  in Newtonian Gravitation and Cosmology. Exact solutions and all asymptotic cosmological behaviour are found for universe with  $G \propto t^m$ .

A key object in dark energy investigation is the equation of state parameter  $\omega$ , which relates pressure and density through an equation of state of the form  $p = \omega\rho$ . Due to lack of observational evidence in making a distinction between constant and variable  $\omega$ , usually the equation of state parameter is considered as a constant (Kujat et al. (2002), Bartelmann et al. (2005)) with values  $0, \frac{1}{3}, -1$  and  $+1$  for dust, radiation, vacuum fluid and stiff fluid dominated Universe respectively. But in general,  $\omega$  is a function of time or redshift (Chevron and Zhuravlev (2000), Zhuravlev (2001), Peebles and Ratra (2003), Das et al. (2005)). For instance, quintessence models involving scalar fields give rise to time-dependent  $\omega$  (Ratra and Peebles (1988), Turner and White (1997), Caldwell et al. (1998), Liddle and Scherrer (1999), Steinhardt et al. (1999)). So, there is enough ground for considering  $\omega$  as time-dependent for a better understanding of the cosmic evolution.

A number of authors have argued in favor of the dependence  $\Lambda \sim t^{-2}$  first expressed by Bertolami (1986) and later by several authors (Berman (1990), Beesham (1986b), Singh et al. (1998), Gasperini (1987), Khadekar et al. (2006)) in different context. Motivation with the work of Ibotombi (2007) and Mukhopadhyay et al. (arXiv:0711.4800v1, (2007)), in this work we studied 5D Kaluza-Klein type metric with perfect fluid and variable  $G$  and  $\Lambda$ .

We have obtained exact solution for Zeldovich fluid models satisfying  $G = G_0(\frac{R}{R_0})^m$  with global equation of state of the form  $p = \frac{1}{3}\phi\rho$ , where  $\phi$  is a function of scale factor  $R$ . In the second part of the paper we have also studied two variable  $\Lambda$  model of the form  $\Lambda \sim (\frac{\dot{R}}{R})^2$  and  $\Lambda \sim \rho$  under the assumption that the equation of state parameter  $\omega$  is a function of time. The possibility of signature flip of the deceleration parameter  $q$  is also shown in the framework of Kaluza-Klein theory of gravitation.

## 2. FIELD EQUATIONS

We consider the 5D Robertson-Walker metric

$$ds^2 = dt^2 - R^2(t) \left[ \frac{dr^2}{(1 - kr^2)} + r^2(d\theta^2 + \sin^2\theta d\phi^2) \right] + A^2(t) d\psi^2, \quad (1)$$

where  $R(t)$  is the scale factor,  $A(t) = R^n$  and  $k = 0, -1$  or  $+1$  is the curvature parameter for flat, open and closed universe, respectively. The universe is assumed to be filled with distribution of matter represented by energy-momentum tensor of a perfect fluid

$$T_{ij} = (p + \rho)u_i u_j - p g_{ij}, \quad (2)$$

where,  $\rho$  is the energy density of the cosmic matter and  $p$  is its pressure and  $u_i$  is the five velocity vector such that  $u_i u^i = 1$ .

The Einstein field equations are given by

$$R_{ij} - \frac{1}{2}g_{ij}R = -8\pi G(t) \left[ T_{ij} - \frac{\Lambda(t)}{8\pi G} g_{ij} \right], \quad (3)$$

where the cosmological term  $\Lambda$  is time-dependent and  $c$ , the velocity of light in vacuum is assumed to be unity.

The conservation equation for variable  $G$  and  $\Lambda$  is given by

$$\dot{\rho} + (3+n)\frac{\dot{R}}{R}(p + \rho) = - \left( \frac{\dot{G}}{G}\rho + \frac{\dot{\Lambda}}{8\pi G} \right). \quad (4)$$

Using co-moving co-ordinates  $u^i = (1, 0, 0, 0, 0)$  in (2) and with metric (1), the Einstein field equations become

$$8\pi G\rho = 3 \left[ (n+1)\frac{\dot{R}^2}{R^2} + \frac{k}{R^2} \right] - \Lambda(t), \quad (5)$$

$$8\pi Gp = -(n+2)\frac{\ddot{R}}{R} - (n^2 + n + 1)\frac{\dot{R}^2}{R^2} - \frac{k}{R^2} + \Lambda(t), \quad (6)$$

$$8\pi Gp = -3 \left( \frac{\ddot{R}}{R} + \frac{\dot{R}^2}{R^2} + \frac{k}{R^2} \right) + \Lambda(t). \quad (7)$$

where dot ( $\dot{\phantom{x}}$ ) denotes derivative with respect to  $t$ . The usual conservation law yields (i.e.  $T_{;j}^{ij} = 0$ )

$$\dot{\rho} + (3+n)(\rho + p)\frac{\dot{R}}{R} = 0. \quad (8)$$

Using Eq.(8) in Eq.(4), we have

$$8\pi\dot{G}\rho + \dot{\Lambda} = 0. \quad (9)$$

Equations (5), (6) and (9) are the fundamental equations and they reduce to standard Friedmann cosmology when  $G$  and  $\Lambda$  are constants. Equations (5) and (6) may be written as

$$3(n+2)\ddot{R} = -8\pi GR(3p+\rho) - 3n^2\frac{\dot{R}^2}{R} + 2\Lambda R, \quad (10)$$

$$3(n+1)\dot{R}^2 = 8\pi GR^2\left[\rho + \frac{\Lambda}{8\pi G}\right] - 3k. \quad (11)$$

Eq.(8) can also be expressed as

$$\frac{d}{dt}(\rho R^{n+3}) + p\frac{d}{dt}(R^{n+3}) = 0. \quad (12)$$

Equations (5), (9) and (12) are independent and they will be used as fundamental. Once the problem is determined, the integration constants are characterized by the observable parameters

$$H_0 = \frac{\dot{R}_0}{R_0}, \quad (13)$$

$$\sigma_0 = \frac{4\pi}{3} \frac{G_0\rho_0}{H_0^2}, \quad (14)$$

$$q_0 = -\frac{\ddot{R}_0}{R_0 H_0^2}, \quad (15)$$

$$\epsilon_0 = \frac{p_0}{\rho_0}, \quad (16)$$

which must satisfy Einstein's equations at present cosmic time  $t_0$ :

$$\Lambda_0 = 3H_0^2 \left[ \sigma_0(3\epsilon_0 + 1) - \frac{(n+2)}{2}q_0 + \frac{n^2}{2} \right], \quad (17)$$

$$\frac{k}{R_0^2} = H_0^2 \left[ 3(1 + \epsilon_0)\sigma_0 - \frac{(n+2)}{2}q_0 + \frac{(n^2 - 2n - 2)}{2} \right], \quad (18)$$

and the conservation Eq. (9) can be written as

$$\dot{\Lambda}_0 G_0 + 6\dot{G}_0 H_0^2 \sigma_0 = 0. \quad (19)$$

### 3. SOLUTIONS OF FIELD EQUATIONS

We find out the solutions of the field equations for two different equation of state: (i)  $p = \frac{1}{3}\rho\phi$  and (ii)  $p = \omega\rho$

#### 3.1. CASE (I)

We assume the global equation of state

$$p = \frac{1}{3}\rho\phi, \quad (20)$$

where  $\phi$  is a function of the scale factor  $R$ . From Eq.(12) and Eq.(20) we obtain

$$\frac{1}{\psi} \frac{d\psi}{dR} + \frac{(n+3)}{3} \frac{\phi}{R} = 0, \quad (21)$$

where

$$\psi = \rho R^{n+3}. \quad (22)$$

Equation (21) be the first condition to determine the problem; either  $\phi$  or  $\psi$  may be in term of arbitrary function. If  $\phi$  is a given explicit function of  $R$ , then Eq.(20) is determined and  $\psi$  follows from Eq.(21)

$$\psi = \psi_0 \exp \left[ - \int \frac{(n+3)}{3} \frac{\phi}{R} dR \right]. \quad (23)$$

If  $\psi$  is given function, from Eq.(20) we get  $\phi$  as

$$\phi = - \frac{3}{(n+3)} \frac{R}{\psi} \frac{d\psi}{dR}. \quad (24)$$

Substitute the value of  $\psi$  from Eq.(22) in the Friedmann's Eq.(5) we get

$$3(n+1)\dot{R}^2 = 8\pi G\psi R^{-(n+1)} + \Lambda R^2 - 3k. \quad (25)$$

Eqs. (9) and (22) with  $\frac{d}{dt} = (\dot{R} \frac{d}{dR})$  give

$$8\pi \frac{dG}{dR} + \psi^{-1} R^{n+3} \frac{d\Lambda}{dR} = 0. \quad (26)$$

If  $G(R)$  is given then after integrating from Eq.(26) we get  $\Lambda(R)$  and from Eq.(25) we get  $R = R(t)$  and the problem is solved. Similarly if  $\Lambda(R)$  may be given instead of  $G(R)$  derives from Eq.(26) we get  $G(R)$  and then from Eq. (25) we get  $R = R(t)$ .

### 3.1.1. Zeldovich fluid satisfying $G = G_0(\frac{R}{R_0})^m$

To solve Eq.(26) for Zeldovich fluid with  $\phi = 3$ . In this case (23) gives,

$$\psi = \rho_0 \left( \frac{R_0}{R} \right)^{n+3}. \quad (27)$$

Substituting  $\psi$  from (27) into (26), we have

$$\Lambda = \Lambda_0 + B_m \left[ 1 - \left( \frac{R}{R_0} \right)^{[m-2(n+3)]} \right] R_0^{-(n+3)}, \quad (28)$$

where,

$$B_m = \frac{6m}{[m-2(n+3)]} \sigma_0 H_0^2, \quad (29)$$

for  $m \neq 2(n+3)$ ,  $B_m$  is a parameter related to the integration constant of Eq.(26). From Eq.(17),

$$\Lambda_0 = 3H_0^2 \left[ 4\sigma_0 - \frac{(n+2)}{2} q_0 + \frac{n^2}{2} \right]. \quad (30)$$

Taking into account (27-28), Friedmann's Eq. (25) takes the form

$$\dot{R}^2 = \alpha_n R^{m-2(n+2)} + \beta_n R^2 - \frac{1}{(n+1)} k, \quad (31)$$

where

$$\alpha_n = \frac{-4(n+3)}{(n+1)(m-2(n+3))} H_0^2 \sigma_0 R_0^{(n+3)-m}, \quad (32)$$

$$\beta_n = \frac{H_0^2}{(n+1)} \left[ \left( 4 + \frac{2m}{(m-2(n+3))} R_0^{-(n+3)} \right) \sigma_0 - \frac{(n+2)}{2} q_0 \right]. \quad (33)$$

Finally the equation for the parameter (18) reduces to

$$\frac{k}{R_0^2} = H_0^2 \left[ 6\sigma_0 - \frac{(n+2)}{2} q_0 + \frac{(n^2-2n-2)}{2} \right]. \quad (34)$$

and (19) is also satisfied.

The case  $m < 2(n+3)$  implies  $B_m < 0$  in Eq.(29) and  $\alpha_n > 0$  in Eq.(32) and vice-versa;  $\beta_n < (\geq) 0$  according to  $m, n, \sigma_0$  and  $q_0$  combine in Eq.(33);  $\Lambda_0 < (\geq) 0$  as  $\sigma_0 < (\geq) (\frac{(n+2)}{2} q_0 - \frac{n^2}{2})$  as given by Eq. (30). From Eq.(34) it is observed that for the curvature parameter  $k = +1, 0, -1$  we get  $[6\sigma_0 - \frac{(n+2)}{2} q_0 + \frac{(n^2-2n-2)}{2}] < (\geq) 0$ . The models are completely characterized by the set of parameters  $(H_0, G_0, \sigma_0, q_0, m)$  with  $m \neq 2(n+3)$ .

## 3.2. CASE (II)

Let us choose the barotropic equation of state

$$p = \omega \rho. \quad (35)$$

Here, we assume that the equation of state parameter  $\omega$  is time-dependent i. e.  $\omega = \omega(t)$  such that  $\omega = (\frac{t}{\tau})^a - 1$  where  $\tau$  is a constant having dimension of time. Field equations (5-7) can also be expressed as

$$3(n+1)H^2 + \frac{3k}{R^2} = 8\pi G\rho + \Lambda(t), \quad (36)$$

$$3(n+1)H^2 + 3(n+1)\dot{H} = -8\pi G[(n+1)p + \rho] - \frac{3nk}{R^2} + n\Lambda(t). \quad (37)$$

From Eq. (35), for flat universe ( $k = 0$ ), we get

$$\rho = \frac{3(n+1)H^2 - \Lambda(t)}{8\pi G}. \quad (38)$$

Using Eq. (37) and Eq.(38) in Eq. (36) we get the differential equation

$$\frac{dH}{dt} = \frac{(1+\omega)\Lambda}{3} + [(n+1)\omega - 2]H^2. \quad (39)$$

To solve Eq. (39) we assume two variable  $\Lambda$  model:  $\Lambda = 3\alpha H^2$  and  $\Lambda = 8\pi G\gamma\rho$ .

**3.2.1. Case (i):  $\Lambda = 3\alpha H^2$** 

For this case Eq. (39) reduces to

$$\frac{dH}{H^2} = \left[ \frac{(n+\alpha+1)t^a}{\tau^a} - (n+3) \right] dt. \quad (40)$$

After solving equation (40) we get,

$$H = \frac{(a+1)\tau^a}{[(n+3)(a+1)t\tau^a - (n+\alpha+1)t^{(a+1)}]}, \quad (41)$$

writing  $H = \frac{\dot{R}}{R}$  in Eq. (41) and integrating it further we get the solution set as

$$R(t) = C_2 \left[ (n+3)(a+1)\tau^a t^{-a} - (n+\alpha+1) \right]^{-\frac{1}{a(n+3)}}, \quad (42)$$

$$\rho(t) = \frac{3(n-\alpha+1)(a+1)^2\tau^{2a}}{8\pi G} \left[ (n+3)(a+1)\tau^a t - (n+\alpha+1)t^{(a+1)} \right]^{-2}, \quad (43)$$

$$\Lambda(t) = \frac{3\alpha(a+1)^2\tau^{2a}}{\left[(n+3)(a+1)\tau^at - (n+\alpha+1)t^{(a+1)}\right]^2}, \quad (44)$$

where  $C_2$  is an integration constant. If  $a = 0$  then  $\omega = 0$  and  $\tau = 1$  but Eq. (42) indicates that  $a$  can not be equal to zero for physical validity.

Again, using Eqs. (38) and (41) we get

$$\frac{\alpha}{(n+1)} = 1 - \Omega_m = \Omega_\Lambda, \quad (45)$$

where, in absence of any curvature, matter density  $\Omega_m$  and dark energy density  $\Omega_\Lambda$  are related by the equation

$$\Omega_m + \Omega_\Lambda = 1. \quad (46)$$

### 3.2.2. Case (ii): $\Lambda = 8\pi G\gamma\rho$

For this case Eq. (39) can be written as

$$\frac{dH}{dt} = \left[ \left( \frac{1+2\gamma}{1+\gamma} \right) \left( \frac{t}{\tau} \right)^a (n+1) - (n+3) \right] H^2. \quad (47)$$

After solving Eq. (47) we get,

$$H = \frac{(1+\gamma)(a+1)\tau^a}{\left[(n+3)(1+\gamma)(a+1)\tau^at - (1+2\gamma)(n+1)t^{a+1}\right]}. \quad (48)$$

Using  $H = \frac{\dot{R}}{R}$  in eq.(48) and integrating we get

$$R(t) = C_3 \left[ (n+3)(1+\gamma)(a+1)\tau^at^{-a} - (1+2\gamma)(n+1) \right]^{-\frac{1}{a(n+3)}}, \quad (49)$$

$$\rho(t) = \frac{3(n+1)}{8\pi G} \frac{(1+\gamma)(a+1)^2\tau^{2a}}{\left[(n+3)(1+\gamma)(a+1)\tau^at - (1+2\gamma)(n+1)t^{(a+1)}\right]^2}, \quad (50)$$

$$\Lambda(t) = \frac{3(n+1)\gamma(1+\gamma)(a+1)^2\tau^{2a}}{\left[(n+3)(1+\gamma)(a+1)\tau^at - (1+2\gamma)(n+1)t^{(a+1)}\right]^2}, \quad (51)$$

where  $C_3$  is an integration constant. Eq. (49) shows that for physical validity  $a \neq 0$ . Again from the field equation we can easily find that  $\gamma$  is related to  $\Omega_m$  and  $\Omega_\Lambda$  through the relation

$$\gamma = \frac{\Omega_\Lambda}{\Omega_m}. \quad (52)$$



#### 4. CONCLUSION

In this paper by considering the gravity with  $G$  and  $\Lambda$  a coupling constant of Einstein field equations with usual conservation laws ( $T^i_{;j} = 0$ ), we obtained the exact solution of the field equations. It is shown that the field equations for perfect fluid cosmology are identical to Einstein equations for  $G$  and  $\Lambda$  including Eq. (12). It is also observed that, the additional conservation Eq. (9) gives the coupling of scalar field with matter.

In the case (I) by introducing the general method of solving the cosmological field equations using a global equation of state of the form  $p = \frac{1}{3}\rho\phi$ , without loss of generality, we find the exact solutions for Zeldovich matter distribution. It is observed that from Eq. (29)  $B_m < 0$  for the case  $m < 2(n+3)$  and  $\Lambda_0 < (\geq) 0$  as  $\sigma_0 < (\geq) \left(\frac{(n+2)}{2}q_0 - \frac{n^2}{2}\right)$ . Similarly  $\left[6\sigma_0 - \frac{(n+2)}{2}q_0 + \frac{(n^2-2n-2)}{2}\right] < (\geq) 0$  depends on the value of curvature parameter  $k$ .

In the case (II), by using equation of state of the form  $p = \omega\rho$ , we again find out the exact solutions of the field equations for two different cases:  $\Lambda = 3\alpha H^2$  and  $\Lambda = 8\pi G\gamma\rho$ . By selecting a simple power law expression of  $t$  for the equation of state parameter  $\omega$ , equivalence of model  $\Lambda \sim (\frac{\dot{R}}{R})^2$  and  $\Lambda \sim \rho$  has been established in the frame work of Kaluza-Klein theory of gravitation. With the help of Eqs. (45) and (52) it is easy to show that Eqs. (42) and (49) are differ by constant while Eqs. (43) and (44) become identical with the Eqs. (50) and (51) respectively. This implies that  $\Lambda \sim (\frac{\dot{R}}{R})^2$  and  $\Lambda \sim \rho$  are equivalent for five dimensional space time. Using Eq. (41) and Eq. (45), we obtain

$$q = - \left[ 1 - \left[ (n+3) - (n+1)(2 - \Omega_m) \left( \frac{t}{\tau} \right)^a \right] \right]. \quad (53)$$

Eq. (53) shows that  $q$  is time dependent and hence may be change its sign during cosmic evolution. It has also been possible to show that the sought for signature flipping of deceleration parameter  $q$  can be obtained by a suitable choice of  $a$ .

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