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CREATION FIELD COSMOLOGICAL MODELS FOR BAROTROPIC FLUID DISTRIBUTION WITH VARIABLE G AND Λ IN FRW SPACETIME

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Abstract : The present work deals with the study of creation field cosmological models for barotropic fluid distribution with variable gravitational constant (G) and cosmological constant (Lambda) in FRW space-time. For deterministic models of the universe, we assume our laws of variation as Lamda is proportional to R(Square power-2) and G proportional to R(Square power n) where R is scale factor and n < 0. The models satisfy conservation equation and creation field increases with time. The singularity, flatness and horizon problem are discussed. The other physical aspects like accelerating behaviour of the models are also discussed. One of the model (39) represents not only expanding universe but also accelerating universe (deceleration parameter q < 0) which match with the result of present day observations. The other model (56) represents Milne Universe which presents linear evolution of scale factor with time that solves age and horizon problems of matter dominated universe. Lastly, the other physical aspects are also discussed. The actions for normalisation of creation field and variable G, Λ are presented.

Keywords Creation field, cosmology, barotropic fluid, variable G and Λ

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1. Introduction

A barotropic fluid is a fluid where density is function of pressure only and vice-versa. The barotropic fluid model is a useful model of fluid behaviour in wide variety of scientific fields from metreology to Astrophysics. In astrophysics, barotropic fluids are important in the study of inter stellar medium. One of the example of barotropic fluid is barotropic layers of oceans.

Dark matter is stuff in space that has gravity but it is invisible glue that holds the universe together. The mysterious material is all around us, making up most of the matter in the universe. Dark matter also acts like gravitational glue. It binds together clusters of galaxies. Without dark matter, our universe would look nothing like the way it does now.

There would be no galaxies, no stars, no planets and therefore no life. It does not interact with electromagnetic force. This means it does not absorb, reflect or emit light, making it extremely hard to spot. In fact it refers to the existence of dark matter only from gravitational effect.

Hoyle and Narlikar [16] introduced creation field cosmology which provides natural solutions of singularity, horizon and flatness problems as mentioned in Narlikar and Padmanabhan[18]. Creation field cosmology does not violate conservation of energy and have negative energy mode. Therefore, if a model explains the creation of positive energy without violating conservation of energy then it is justified for creation field cosmology with negative energy field. Bali [3] continued the study on avoidance of singularity in creation field cosmology in the exterior of spherically symmetric space-time.

The gravitational constant (G) plays a significant role of coupling constant between geometry and matter in Einstein's general theory of relativity. Therefore, it is interesting to consider this constant as a function of time in an evolving universe. Dirac [11] suggested the variation of G with time on the basis of large number hypothesis. To achieve unification of gravitation and elementary particle physics or to incorporate Mach's principle in general relativity. Many attempts have been proposed by several researchers [7, 14, 14, 8, 10, 5].

By incorporating particle physics into Einstein's theory of gravitation, the interesting approach is to explain the cosmological constant (Λ) in terms of quantum mechanics and physics of vacuum as mentioned by Zel'dovich [21]. Frieman et al. [12] investigated that we have entered an era dominated by dark energy (cosmological term). In Einstein's field equation, the non-trivial role of vacuum generates a cosmological term which leads to inflationary scenario. The present day observations on the smallness of the cosmological constant ($\Lambda_0 \sim 10^{-122}$) support to assume the cosmological constant is time dependent. Thus, the cosmological models linking the variation of the cosmological constant and having the form of Einstein field equations that remains unchanged, have been studied by many authors [6, 9, 24].

In an earlier paper, Bali and Kumawat [1] investigated creation field cosmological models with variable G and Λ for dust distribution in FRW space-time. In this paper, we have investigated creation field cosmological models for barotropic fluid distribution with variable G and Λ in FRW space-time. The special cases for dust, radiation, with singularity, horizon and flatness problem are also discussed.

2. Normalisation of C-field

In 1963, Hoyle and Narlikar [15] introduced a Scalar field C in the action, namely the creation field. The action for Hoyle-Narlikar theory is taken as

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} - L^{matter} - \frac{1}{2}fC^iC_i + fC_iJ^i\right] \tag{1}$$

where f is coupling constant between matter and creation field, $C_i = \frac{\partial C}{\partial x^i}$ and J^i the mass current defined as

$$J^i = \rho u^i \tag{2}$$

Now integrating 3-space volume $d^3x\sqrt{-g}$, we have

$$\int d^4x\sqrt{-g}fC_iJ^i = \Sigma mf\int C_iu^ids = \Sigma mf\int C_idx^i$$

Also $\delta\int C_idx^i = \int[\delta C_idx^i + C_i\delta(dx^i)]$

$$= \int[\delta x^j\partial_jC_idx^i + C_id(\delta x^i)]$$

$$= \int[\delta x^j\partial_jC_idx^i - dx^j\partial_jC_i\delta x^i]$$

$$= 0$$

It shows that the 4th term in action given by (1) does not contribute.

Thus (1) leads to

$$\delta S = \int d^4x\sqrt{-g}[-fC^i\delta C_i + f\delta C_iJ^i] = 0$$

$$= -[C^i\delta C] + \int d^4x\sqrt{-g}[\Box C\delta C + [\delta CJ^i]$$

$$-\int d^4x\sqrt{-g}J^i_{;i}\,\delta C = 0$$

which can be written as

$$\int d^4x\sqrt{-g}[\Box C - J^i_{;i}]\delta C = 0$$

as $[\delta C]_\Sigma = 0$ and $J^i_{;i} = \left(\sqrt{-g}\right)^{-1}\partial_i\left(\sqrt{-g}J^i\right)$ (3)

Equation (2) can be written as

$$\Box C = J^i_{;i}$$

Variation of the 3rd term in (1) with respect to g_{ij}, leads to

$$\delta S = \frac{1}{2}f\int d^4x\sqrt{-g}\left[-C_iC_j + \frac{1}{2}g_{ij}C^kC_k\right]\delta g^{ij}$$

Thus, from equation (1), the creation field equations are obtained as

$$R_{ij} - \frac{1}{2}Rg_{ij} = -8\pi G\left[T^{matter}_{ij} - f\left(C_iC_j - \frac{1}{2}g_{ij}C^kC_k\right)\right] \tag{4}$$

As $\left(R^i_j - \frac{1}{2}\delta^i_j R\right)_{;i} = 0$, we have

$$\left[(\rho + p)u^i u_j - p g^i_j - f\left(C^i C_j - \frac{1}{2}\delta^i_j C^k C_k\right)\right]_{;i} = 0 \tag{5}$$

Equation (5) yields

$$\left[(\rho + p)u^i u_j - p g^i_j - f\left(C^i C_j - \frac{1}{2}\delta^i_j C^k C_k\right)\right] = 0 \tag{6}$$

as $u^i u_{j;i} = 0$ being geodesic equation. Thus equation (6) leads to

$$\left[(\rho + p) - p g^i_j\right] u^i_{;i} u_j = f C^i_{;i} C_j \tag{7}$$

Connecting (2) and (7), we have

$$u_j = f C_j \tag{8}$$

Thus putting f = 1, the creation field can be normalised.

Introducing the result (8) in field equation (4) we get

$$R_{ij} - \frac{1}{2} R g_{ij} = -8\pi G\left[T^{\text{matter}}_{ij} - f\left(C^i C_j - \frac{1}{2}\delta^i_j C^k C_k\right)\right]$$

3. Action for Variable G and Λ of the Model

The action for our model is defined as mentioned by Krori et al. [17]

$$S = \int d^4 x L = \int d^4 x \left[\sqrt{-g}\left\{\frac{R}{G} + F(G)\right\} + Lm\right] \tag{9}$$

Where G is Newton's gravitational constant and F(G) is an arbitrary function of G while Lm is a matter Langrangian. From Eurler-Lagrange equation

$$\frac{\partial L}{\partial G} = \nabla_\mu \frac{\partial L}{\partial(\partial_\mu G)} \tag{10}$$

We obtain the following equation

$$\frac{\partial F}{\partial G} = \frac{R}{G^2} \tag{11}$$

Taking variation with respect to g_{uv}, equation (10) leads to

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G(t) T_{\mu\nu} + g_{\mu\nu}\left(\frac{1}{2} G F(G)\right) \tag{12}$$

Assuming $\frac{1}{2}GF(G) = \Lambda(t)$ (13)

Equation (12) leads to

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G(t)T_{\mu\nu} + g_{\mu\nu}\Lambda(t) \tag{14}$$

4. Metric and Field Equations

We consider the homogeneous and isotropic FRW space-time as

$$ds^2 = dt^2 - R^2(t)\left[\frac{dr^2}{1 - Kr^2} + r^2 d\theta^2 + r^2\sin^2\theta\, d\phi^2\right] \tag{15}$$

Where $R(t)$ is the scale factor and $K = -1,0,1$ is curvature parameter for spatially open, flat and closed universes respectively.

Einstein’s modified field equations by the introduction of C-field with variable G and Λ, are given by

$$R_i^j - \frac{1}{2}R\, g_i^j = -8\pi G[{}^m T_i^j + {}^C T_i^j] + \Lambda g_i^j \tag{16}$$

Using renormalization group, variable G behaves a minimally coupled field (not a Scalar tensor theory) and variable Λ can be interpreted as a potential function. The point Lagrangian for this model in the background of homogeneous and isotropic flat FLRW space-time model experiences point like Noether symmetry and equivalent potential function Λ (G) is determined. (arxiv:1911.09520v1 as given by Santu et al. (2019)

Where energy momentum tensor for matter ${}^m T_j^i$ and energy momentum tensor for creation field ${}^C T_j^i$ are given by

$${}^m T_j^i = (\rho + p)v_i v^j - p g_i^j \tag{17}$$

$${}^C T_j^i = -f\left(C_i C^j - \frac{1}{2}g_i^j C^\alpha C_\alpha\right) \tag{18}$$

where $f > 0$ and $C_i = \frac{dC}{dx^i}$. We assume the coordinates to be co-moving so $g_{ij}\nu^i\nu^j = 1$, $\nu^1 = 0$, $\nu^2 = \nu^3 =$ and $\nu^4 = 1$. Now the field equations (14) for metric (15) lead to

$$\frac{3\dot{R}^2}{R^2} + \frac{3K}{R^2} = 8\pi G\left[\rho - \frac{1}{2}f\,\dot{C}^2\right] + \Lambda \tag{19}$$

$$\frac{2\ddot{R}}{R} + \frac{\dot{R}^2}{R^2} + \frac{K}{R^2} = 8\pi G\left[\frac{1}{2} f\,\dot{C}^2 - p\right] + \Lambda \tag{20}$$

5. Solution of Field Equations

The conservation equation

$$[8\pi G\, T_i^j + \Lambda g_i^j]_{;j} = 0 \tag{21}$$

leads to

$$8\pi\dot{G}\left(\rho - \frac{1}{2} f\, \dot{C}^2\right) + 8\pi G\left[\dot{\rho} - f\dot{C}\ddot{C} - 3f\dot{C}^2\frac{\dot{R}}{R} + 3(\rho + p)\frac{\dot{R}}{R}\right] + \dot{\Lambda} = 0 \tag{22}$$

Where over head dot indicates partial derivative with respect to cosmic time t.

Equation (22) yields $\dot{C} = 1$ when used in source equation shown in equation (45) (Please see (40) and (44))

Using $\dot{C} = 1$, equation (19) leads to

$$\frac{3\dot{R}^2}{R^2} + \frac{3K}{R^2} = 8\pi G\, \rho - 4\pi G f + \Lambda \tag{23}$$

Using $\dot{C} = 1$ and barotropic condition $p = \gamma\rho$ $(0 \le \gamma \le 1)$ in equation (20), we have

$$\frac{2\ddot{R}}{R} + \frac{\dot{R}^2}{R^2} + \frac{K}{R^2} = 4\pi G f - 8\pi G \gamma\rho + \Lambda \tag{24}$$

Equations (23) and (24) lead to

$$\frac{2\ddot{R}}{R} + (1+3\gamma)\frac{\dot{R}^2}{R^2} + (1+3\gamma)\frac{K}{R^2} = 4\pi G f\,(1-\gamma) + (1+\gamma)\Lambda \tag{25}$$

To get the deterministic solution in terms of cosmic time t, we assume

$$G = \ell R^n \tag{26}$$

Where l is positive constant and $n < 0$.

and $\Lambda = \dfrac{\alpha}{R^2}$ as considered by Chen and Wu [9] (27)

where n and α are constants and R the scale factor.

Equations (25), (26) and (27) lead to

$$2\ddot{R} + (1+3\gamma)\frac{\dot{R}^2}{R} = 4\pi f\,(1-\gamma)R^{n+1} + \frac{[(1+\gamma)\alpha - (1+3\gamma)K]}{R} \tag{28}$$

To get the solution of equation (28), we assume $\dot{R} = F(R)$. This leads to $\ddot{R} = F F'$ with $F' = \frac{dF}{dR}$. Thus equation (28) leads to

$$\frac{dF^2}{dR} + \frac{(1+3\gamma)F^2}{R} = 4\pi f(1-\gamma)R^{n+1} - \frac{[(1+3\gamma)K - (1+\gamma)\alpha]}{R} \tag{29}$$

which leads to

$$F^2 = \frac{4\pi f(1-\gamma)R^{n+2}}{n+3\gamma+3} - \frac{[(1+3\gamma)K - (1+\gamma)\alpha]}{(1+3\gamma)} \tag{30}$$

where constant of integration has been taken zero for simplicity.

From equation (30), we have

$$\frac{dR}{\sqrt{R^{n+2} - \frac{(n+3\gamma+3)[(1+3\gamma)K - (1+\gamma)\alpha]}{4\pi f(1-\gamma)(1+3\gamma)}}} = \sqrt{\frac{4\pi f(1-\gamma)}{(n+3\gamma+3)}}\, dt \tag{31}$$

To obtain the deterministic value of R in terms of cosmic time t, we consider two cases

Case I: n = -1

Equation (31) for n = -1leads to

$$\frac{dR}{\sqrt{R - \frac{(3\gamma+2)[(1+3\gamma)K - (1+\gamma)\alpha]}{4\pi f(1-\gamma)(1+3\gamma)}}} = \sqrt{\frac{4\pi f(1-\gamma)}{(3\gamma+2)}}\, dt \tag{32}$$

From equation (32), we have

$$R = t^2 + \beta \tag{33}$$

where

$$a = \frac{1}{2}\sqrt{\frac{4\pi f(1-\gamma)}{(3\gamma+2)}} = 1 \tag{34}$$

$$b = \frac{N}{2} = 0, \; \beta = \frac{(3\gamma+2)\left[(1+3\gamma)K - (1+\gamma)\alpha\right]}{4\pi f(1-\gamma)(1+3\gamma)} \tag{35}$$

where N is a constant of integration and $\gamma \neq 1$. Thus, we have

$$G = \ell R^{-1} = \ell\left(t^2+\beta\right)^{-1} \tag{36}$$

$$\Lambda = \alpha R^{-2} = \alpha\left(t^2+\beta\right)^{-2} \tag{37}$$

From equations (23), (33), (36) and (37), we have

$$8\pi\rho = \frac{12t^2+3K-\alpha}{t^2+\beta} + 4\pi f \tag{38}$$

After using the value of R given by (33), the metric (15) leads to

$$ds^2 = dt^2 - (t^2+\beta)^2\left[\frac{dr^2}{1-Kr^2} + r^2 d\theta^2 + r^2\sin^2\theta d\varphi^2\right] \tag{39}$$

Now equation (22) leads to

$$8\pi\dot{G}\left(\rho - \frac{1}{2} f\,\dot{C}^2\right) + 8\pi G\left[\dot{\rho} - f\dot{C}\ddot{C} - 3f\dot{C}^2\,\frac{\dot{R}}{R} + 3\rho(1+\gamma)\frac{\dot{R}}{R}\right] + \dot{\Lambda} = 0 \tag{40}$$

Using equations (33), (36), (37) and (38) into equation (40), we get

$$\frac{d\dot{C}^2}{dt} + \frac{10t}{\left\{t^2+\beta\right\}}\dot{C}^2 =$$

$$\frac{24t^3(3\gamma+2) + 2t(3K-\alpha)(3\gamma+1) + 24t\,\frac{(3\gamma+2)[(1+3\gamma)K-(1+\gamma)\alpha]}{4\pi f(1-\gamma)(1+3\gamma)} - 4\alpha t}{4\pi f\left(t^2+\beta\right)^2} \tag{41}$$

$$+\frac{2t(3\gamma+2)}{\left(t^2+\beta\right)}$$

Equation (41) leads to

$$\dot{C}^2\left\{t^2+\beta\right\}^5 = \frac{1}{4\pi f}\int\left[24t^3(3\gamma+2) + 2t(3K-\alpha)(3\gamma+1) + 24\beta t - 4\alpha t\right]$$
$$\times\left(t^2+\beta\right)^3 dt + \int 2t(3\gamma+2)\left(t^2+\beta\right)^4 dt \tag{42}$$

From equation (42), we have

$$\dot{C}^2\left(t^2+\beta\right)^5 = \frac{(3\gamma+2)}{5}\left(\frac{12}{4\pi f}+1\right)\left(t^2+\beta\right)^5 +$$
$$\frac{1}{16\pi f}\left\{-12(3\gamma+1)\beta + (3K-\alpha)(3\gamma+1) - 2\alpha\right\}\left(t^2+\beta\right)^5 \tag{43}$$

which leads to

$$\dot{C}^2 = 1 \tag{44}$$

Thus, we have

$$C = t \tag{45}$$

6. Physical and Geometrical Aspects

The homogeneous mass density ρ, gravitational constant G, Cos deceleration parameter (q) the cosmological constant (Λ), the expansion (θ) for the model (39) are given by

$$8\pi\rho = \frac{12t^2 + (3K - \alpha)}{t^2 + \beta} + 4\pi f \tag{46}$$

$$G = \frac{\ell}{t^2 + \beta} \tag{47}$$

$$q = -\left(\frac{t^2 + \beta}{2t^2}\right) \tag{48}$$

$$\Lambda = \frac{\alpha}{\left(t^2 + \beta\right)^2} \tag{49}$$

$$\theta = 3H = \frac{6t}{t^2 + \beta} \tag{50}$$

Case II: n = -2

For n = -2 equation (31) leads to

$$\frac{dR}{\sqrt{1 - \frac{[(1+3\gamma)K - (1+\gamma)\alpha]}{4\pi f(1-\gamma)}}} = \sqrt{\frac{4\pi f(1-\gamma)}{(3\gamma+1)}}\,dt \tag{51}$$

From equation (51), we have

$$R = \left\{\sqrt{\frac{4\pi f\,(1-\gamma) + \left[(1+\gamma)\alpha - (1+3\gamma)K\right]}{(1+3\gamma)}}\,t\right\} = At \tag{52}$$

where $A = \sqrt{\frac{4\pi f\,(1-\gamma) + \left[(1+\gamma)\alpha - (1+3\gamma)K\right]}{(1+3\gamma)}}$

and integral constant is assumed zero for simplicity.

$$G = \frac{\ell}{A^2t^2} \tag{53}$$

$$\Lambda = \frac{\alpha}{A^2t^2} \tag{54}$$

From equations (23), (55), (56) and (57), we have

$$8\pi\rho = \frac{16\pi f + 2\alpha}{1+3\gamma} \tag{55}$$

After using the value of R given by (52), the metric (15) leads to

$$ds^2 = dt^2 - A^2t^2\left[\frac{dr^2}{1-Kr^2} + r^2d\theta^2 + r^2\sin^2\theta d\varphi^2\right] \tag{56}$$

Using equations (52), (53), (54) and (55) into equation (40), we have

$$\dot{C}^2\left(A^4t^4\right) = \left(A^4t^4\right) \tag{57}$$

Now equation (57) gives

$$\dot{C}^2 = 1 \tag{58}$$

which leads to

$$C = t \tag{59}$$

Hence we find $\dot{C} = 1$ which agrees with the value used in the source equation. Thus creation field C is proportional to time t.

The homogeneous mass density ρ, gravitational constant G, and deceleration parameter (q) expansion (θ), cosmological constant (Λ) for the model (56) are given by

$$8\pi\rho = \frac{16\pi f + 2\alpha}{1+3\gamma} \tag{60}$$

$$G = \frac{\ell}{A^2t^2} \tag{61}$$

$$q = 0 \tag{62}$$

$$\theta = 3H = \frac{3}{t} \tag{63}$$

$$\Lambda = \frac{\alpha}{A^2t^2} \tag{64}$$

Now, we discuss event horizon, singularity and flatness problems as

7. Event Horizon

The co-ordinate distance to the horizon $\gamma_H(t)$ is the maximum distance at time t from the infinite past i.e. for the model (39), we have

$$\gamma_H(t) = \int_{-\infty}^{t} \frac{dt}{R(t)} = \int_{0}^{t} \frac{dt}{R(t)} = \int_{0}^{t} \frac{dt}{t^2+\beta} \quad \begin{aligned} &= 0 \text{ when } t = 0 \\ &= \infty \text{ when } t = \pi/2 \end{aligned}$$

i.e. the model (39) has particle horizon at lower limit but has event horizon at upper limit.

For the model (56)

$$\gamma_H(t) = \int_{-\infty}^{t} \frac{dt}{R(t)} = \int_{0}^{t} \frac{dt}{\ell t} = \infty$$

The model (56) has Event horizon at lower limit.

8. Singularity

For an observer at epoch t_0 for the model (39) we have

$$\int_{t_p}^{t_0} R(t)dt = \int_{t_p}^{t_0} (t^2+\beta)dt = -\infty \text{ at } t_p = -\infty$$

and for the model (56),

$$\int_{t_p}^{t_0} R(t)dt = \int_{t_p}^{t_0} Atdt = -\infty \text{ at } t_p = -\infty$$

Thus both the model emerge as non-singular.

9. Flatness

For the model (56), we have

$$|\Omega - 1| = \left|\frac{\rho - \rho_c}{\rho_c}\right| = 10^{-55}$$

Thus the models lead to flatness

where ρ_c = critical density = $\dfrac{3H_0^2}{8\pi G} = 9.47 \times 10^{-27}\,\text{kg}/\text{m}^3$

$G = 6.67 \times 10^{-11}$

10. Conclusion

The spatial volume (R^3) increases with time for both the models representing inflationary scenario. The homogeneous mass density (ρ) for the model (39) is positive and satisfies reality conditions. Also the model (39) represents expanding and accelerating universe which agrees with the result as investigated by Riess et al. [20] and Perlmutter et al. [19]. The cosmological parameter (Λ) helps to solve the problems of steady state theory as mentioned by Hoyle et al. [16]. We also observe that the models (39) and (56) are free from singularity, has event horizon and solves flatness problem in presence of creation field cosmology.

The homogeneous mass for the model (56) density is constant which can be interpreted as when matter moves further apart, it is assumed that more matter is created continuously to maintain the density at constant value as explained in Hoyle & Narlikar [16]. The model (56) represents Milne Universe which presents linear evolution of scale factor with time, solving age and horizon problems of matter dominated universe. The special cases for $\gamma = 0$ (dust), $\gamma = 1/3$ (radiation dominated), r = 1 (stiff fluid) can also be discussed easily.

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