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RESEARCH ARTICLE

KALUZA – KLEIN COSMOLOGICAL MODEL WITH QUARK AND STRANGE QUARK MATTER IN $f(R,T)$ GRAVITY

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Abstract

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In this paper, Kaluza-Klein space-time with quark and strange quark matter in $f(R,T)$ gravity has been studied. The general solutions of the field equations of Kaluza-Klein space-time have been obtained under the assumption of constant deceleration parameter**.** The physical and geometrical aspects of the model are also discussed in details.

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Introduction:-

A fundamental theoretical challenge to gravitational theories has been imposed by the observational data (Reiss *et al.*[1], Perlmutter *et al.*[2], Bernardis *et al.*[3], Hanany *et al.* [4], Padmanabhan [5], Peeble and Ratra[6]) on the late time acceleration of the universe and the existence of the dark matter. Carroll *et al.*[7] explained the presence of a late time cosmic acceleration of the universe in $f(R)$ gravity. Bertolami *et al.*[8] have proposed a generalization of $f(R)$ modified theories of gravity, by including in the theory an explicit coupling of an arbitrary function of the Ricci scalar R with the matter Lagrangian density L_m. Several $f(R)$ gravity models are reviewed by Capozziello *et al.*[9]. The Palatini formulation of the non-minimal geometry-coupling models was considered by Harko *et al.*[10]. Harko and Lobo [11] proposed a maximal extension of the Hilbert-Einstein action assuming the gravitational Lagrangian as an arbitrary function of the Ricci scalar R and of the matter Lagrangian L_m.

Harko *et al.*[12] developed $f(R,T)$ modified theory of gravity, where the gravitational Lagrangian is given by an arbitrary function of the Ricci scalar R and of the trace of the stress-energy tensor T. They have obtained the gravitational field equations in the metric formalism as well as the equations of motion for test particles, which follow from the covariant divergence of the stress-energy tensor. Generally, the gravitational field equations depend on the nature of the matter source. They have presented the field equations of several particular models, corresponding to some explicit forms of the function $f(R,T)$. Reddy *et al.*[13,14] have extended this work for Kaluza-Klein and Bianchi type-III Universe and Adhav [15] for LRS Bianchi type-I Universe in presence of the perfect fluid in $f(R,T)$ gravity.

The theory of five dimensions is due to the idea of Kaluza [16] and Klein [17]. A five dimensional (*5D*) general relativity is the best outcome of an attempt made by these two by using one extra dimension to unify gravity and electro-magnetism. Realistic unification through the Kaluza-Klein approach requires $d = 5$ manifold topology and the spatial extra dimension radius is of Planck length order. According to Wesson [18,19] and Bellini [20], the matter is induced in *4D* by *5D* vacuum theory for studying the cosmology of *5D* with pure geometry in non-compact

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Kaluza-Klein theory. Kaluza-Klein theory is essentially an extension of Einstein's general theory of relativity in five dimensions which is of much interest in particle physics & cosmology.

The number of studies have been done by considering quark matter and strange quark matter in general relativity and other modified theories of gravity (Katore[21], Khadekar*et al*.[22], Mahanta *et al*.[23], Santhikumar *et al*. [24], Caglar *et al*.[25]). Recently, Sahoo *et al*.[26 , 27] have con-structed an anisotropic models with magnetized strange quark matter in $f(R,T)$ gravity by considering some specific parametrization of deceleration parameter. Nagpal *et al*.[28] has been studied magnetized quark matter and strange quark matter distributions in $f(R,T)$ gravity. Recently, Prasad *et al*.[29] considered the bulk viscous fluid for the model in $f(R,T)$ gravity and also Dinesh Chandra Maurya*et al*.[30] have studied Domain walls and quark matter in Bianchi type-V universe with observational constraints in $f(R,T)$ gravity.

In the present paper, Kaluza-Klein cosmological model with quark matter and strange quark matter in $f(R,T)$ theory of gravity has been studied. The general solutions of the field equations of Kaluza-Klein space-time have been obtained under the assumption of constant deceleration parameter in the context of exponential volumetric expansion model. The physical and geometrical aspects of the model are also discussed in detailed.

Gravitational field equations of $f(R,T)$ theory of gravity:-

In $f(R,T)$ theory of gravity, the field equations are obtained from the Hilbert-Einstein type variation principle. The action for this modified theory of gravity is given by

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

where $f(R,T)$ is an arbitrary function of the Ricci scalar R and of the trace T of the stress-energy tensor of the matter $T_{\mu\nu}$ and L_m is the matter Lagrangian.

The corresponding field equations of the $f(R,T)$ gravity is found by varying the action (1) with respect to the metric $g_{\mu\nu}$:

$$f_R(R,T)R_{\mu\nu} - \frac{1}{2}f(R,T)g_{\mu\nu} + (g_{\mu\nu}\Box - \nabla_\mu\nabla_\nu)f_R(R,T) = 8\pi T_{\mu\nu} - f_T(R,T)T_{\mu\nu} - f_T(R,T)\Theta_{\mu\nu} \ , \tag{2}$$

where $f_R(R,T) = \frac{\partial f(R,T)}{\partial R}$, $f_T(R,T) = \frac{\partial f(R,T)}{\partial T}$, $\Box = \nabla^\mu\nabla_\mu$, $\Theta_{\mu\nu} = g^{\alpha\beta}\frac{\delta T_{\alpha\beta}}{\delta g^{\mu\nu}}$; (3)

∇_μ is the covariant derivative and $T_{\mu\nu}$ is the standard matter energy-momentum tensor derived from the Lagrangian L_m.

The stress-energy tensor of matter is

$$T_{\mu\nu} = -\frac{2}{\sqrt{-g}}\frac{\delta\,(\sqrt{-g}L_m)}{\delta g^{\mu\nu}} \ . \tag{4}$$

The tensor $\Theta_{\mu\nu}$ in equation (2) is given by

$$\Theta_{\mu\nu} = -2\,T_{\mu\nu} + g_{\mu\nu}L_m - 2g^{\alpha\beta}\frac{\partial^2 L_m}{\partial g^{\mu\nu}\partial g^{\alpha\beta}} \ , \tag{5}$$

the matter Lagrangian L_m may be chosen as $L_m = -p$, where p is the thermodynamical pressure of matter content of the Universe.

Now, equation (5) gives the variation of the stress-energy tensor as

$$\Theta_{\mu\nu} = -2\,T_{\mu\nu} - p g_{\mu\nu} \quad , \tag{6}$$

Generally, the field equations also depend on (through the tensor $\Theta_{\mu\nu}$) the physical nature of the matter field. Hence, several theoretical models corresponding to different matter sources in $f(R,T)$ gravity can be obtained. Harko *et al.*[12] obtained some particular classes of $f(R,T)$ modified gravity models by specifying functional form of f as

$$\left.\begin{array}{ll} (i) & f(R,T) = R + 2f(T) \\ (ii) & f(R,T) = f_1(R) + f_2(T) \\ (iii) & f(R,T) = f_1(R) + f_2(R)f_3(T) \end{array}\right\}. \tag{7}$$

Harko*et al*. [11] have investigated FRW cosmological models in this theory by choosing appropriate function $f(T)$. They have also discussed the case of scalar fields since scalar fields play a vital role in cosmology. The equations of motion of test particles and a Brans-Dickey type formulation of the model are also presented.

Metric and Field Equations:-

Consider a five-dimensional Kaluza-Klein metric in the form as

$$ds^2 = dt^2 - A^2(t)(dx^2 + dy^2 + dz^2) - B^2(t)d\psi^2 \quad , \tag{8}$$

where $A(t)$ and $B(t)$ are the scale factors (metric tensors) and functions of cosmic time t only and the fifth coordinate ψ is taken to be space-like.

In the present study, we assume that the energy momentum tensor for the quark matter (Aktas *et. al.*[31] , Yilmaz, *et. al.* [32]) in the form as

$$T^{(Quark)}{}_{\mu\nu} = (\rho + p)\ u_\mu u_\nu - p g_{\mu\nu} \quad , \tag{9}$$

where $\rho = \rho_q + B_c$ is the energy density, $p = p_q - B_c$ is pressure of the fluid and $u_\mu = (1,0,0,0,0)$ is the five-velocity vector in the comoving coordinates system which satisfies the condition $u_\mu u^\mu = 1$. Since quark matter behaves nearly perfect fluid (Adams *et al.*[33], Adcox*et al.*[34], Back *et al.*[35], Aktas *et al.*[31], Yilmaz *et al.*[32]). We will use the following equation of state for quark matter in the form as

$$p_q = \varepsilon \rho_q \quad , \quad 0 \le \varepsilon \le 1. \tag{10}$$

Also, the linear equation of state for strange quark matter (Sharma *et al*. [36, 37]) in the form as

$$p = \varepsilon(\rho - \rho_0) \ , \tag{11}$$

where ρ_0 is the energy density at zero pressure and ε is a constant.

When $\varepsilon = \frac{1}{3}$ and $\rho_0 = 4B_c$, the above linear equation of state is reduced to the followingequation of state for strange quark matter in the bag model (Aktas*et al*. [31], Yilmaz *et al*. [32]) as

$$p = \frac{(\rho - 4B_c)}{3} \quad , \tag{12}$$

where B_c is the Bag constant.

In the present paper, we consider Kaluza-Klein cosmological model for the particular choice of $f(R,T)$ given by

$$f(R,T) = R + 2f(T). \tag{13}$$

where the $f(T)$ is an arbitrary function of the trace of the stress-energy tensor of matter.

Using equation (6) & (13) in equation (2) then the gravitational field equation in $f(R,T)$gravity becomes

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi T_{\mu\nu} + 2\,f'(T)T_{\mu\nu} + [2pf'(T) + \ f(T)]g_{\mu\nu} \quad , \tag{14}$$

where prime denotes differentiation with respect to the argument.

Now, In the present work, we choose the function $f(T)$ of the trace of the stress-energy tensor of the matter as

$$f(T) = \lambda T \text{ , where } \lambda \text{ is a constant.} \tag{15}$$

The corresponding field equations (14) for the metric (8) with the help of equations (9) and (15) can be written as

$$3\frac{\dot{A}^2}{A^2} + 3\frac{\dot{A}\dot{B}}{AB} = -(8\pi + 3\lambda)\rho_q + 2\lambda p_q - (8\pi + 5\lambda)B_c \quad , \tag{16}$$

$$2\frac{\ddot{A}}{A} + \frac{\dot{A}^2}{A^2} + 2\frac{\dot{A}\dot{B}}{AB} + \frac{\ddot{B}}{B} = (8\pi + 4\lambda)p_q - \lambda\rho_q - (8\pi + 5\lambda)B_c \quad , \tag{17}$$

$$3\frac{\ddot{A}}{A} + 3\frac{\dot{A}^2}{A^2} = (8\pi + 4\lambda)p_q - \lambda\rho_q - (8\pi + 5\lambda)B_c \quad , \tag{18}$$

where the overhead dot (·) denote derivative with respect to the cosmic time t.

The spatial volume (V) is defined as

$$V = a^4 = A^3 B \quad , \tag{19}$$

where a is the average scale factor.

The directional Hubble parameters in the directions of x, y, z and ψ axes respectively are defined as

$$H_x = H_y = H_z = \frac{\dot{A}}{A} \quad , \quad H_\psi = \frac{\dot{B}}{B} \ . \tag{20}$$

The mean Hubble parameter (H) is given by

$$H = \frac{1}{4}\left(3\frac{\dot{A}}{A} + \frac{\dot{B}}{B}\right). \tag{21}$$

The volumetric deceleration parameter (q) is given by

$$q = -\frac{a\ddot{a}}{\dot{a}^2} \ . \tag{22}$$

The anisotropic parameter (Δ) of the expansionis defined as

$$\Delta = \frac{1}{4}\sum_{i=1}^{4}\left(\frac{H_i - H}{H}\right)^2 , \tag{23}$$

where $H_i (i = 1,2,3,4)$ represent the directional Hubble parameters in the direction of x, y, z and ψ respectively.

The expansion scalar (θ) is defined as

$$\theta = 4H. \tag{24}$$

The Shear scalar (σ^2) is defined as

$$\sigma^2 = \frac{4}{2}\Delta \ H^2 \ . \tag{25}$$

Solutions of the field equations:-

Since there are three highly non-linear equations (16) to (18) with four unknowns A, B, ρ_q and p_q. In order to solve the system completely, we impose a law of variation for the Hubble parameter which was initially proposed by Berman [38] for RW (Robertson-Walker) space-time and yields the constant value of deceleration parameter. Adhav*et al*. [39] used this law for LRS Bianchi type-I metric in creation field cosmology. According to this law, the variation of the mean Hubble parameter for the Kaluza-Klein metric given by

$$H = k(A^3B)^{-m/4} \quad , \tag{26}$$

where $k > 0$ and $m \geq 0$ are constants.

Now, equating equation (21) with (26) and integrating we get

$$V = A^3B = c_1 e^{4kt} \quad , \qquad \text{for } m = 0 \ , \tag{27}$$

and

$$V = A^3B = (mkt + c_2)^{4/m} \quad , \text{for } m \neq 0 \ , \tag{28}$$

where c_1 and c_2 are positive constants of integration.

Using equation (26) with (27) for $m = 0$ and with (28) for $m \neq 0$, the mean Hubble parameters areobtained as

$$H = k \qquad , \qquad \text{for } m = 0 \ , \tag{29}$$

and

$$H = k(mkt + c_2)^{-1} \quad , \quad \text{for } m \neq 0 \ . \tag{30}$$

Using equations (27) and (28) in (22), we get constant values for the deceleration parameter for mean scale factor as

$$q = -1 \qquad , \qquad \text{for } m = 0 \ , \tag{31}$$

and

$$q = m - 1 \quad , \qquad \text{for } m \neq 0. \tag{32}$$

The sign of q indicates whether the model accelerates or not. The positive sign if $q(m > 1)$ corresponds to decelerating models where as the negative sign $-1 \leq q < 0$ for $0 \leq m < 1$ indicates acceleration and $q = 0$ for $m = 1$ corresponds to expansion with constant velocity.

In this paper, we consider the model for $\boldsymbol{m = 0}$, $(\boldsymbol{q = -1})$**:**
(*Exponential Volumetric Expansion Model*)

Subtracting equation (17) from (18) and using mean Hubble parameter from equation (21), we get

$$\frac{d}{dt}\left(\frac{\dot{A}}{A} - \frac{\dot{B}}{B}\right) + \left(\frac{\dot{A}}{A} - \frac{\dot{B}}{B}\right) \ 4H = 0 \ . \tag{33}$$

On integration of equation (33) and considering equation (29), we obtain

$$\left(\frac{\dot{A}}{A} - \frac{\dot{B}}{B}\right) = c_3 e^{-4kt} \quad , \tag{34}$$

where c_3 is constant of integration.

On integration of equation (34) and using equation (27), we get exact values of the scale factors

$$A(t) = \left(\frac{c_1}{c_4}\right)^{\frac{1}{4}} \ e^{\left(kt - \frac{1}{16k\, c_3} \ e^{-4kt}\right)} \quad , \tag{35}$$

$$B(t) = (c_1 c_4^3)^{\frac{1}{4}} \ e^{\left(kt + \frac{3}{16k\, c_3} e^{-4kt}\right)} \quad , \tag{36}$$

where c_1 , c_3 and c_4 are constants of integration.

The spatial volume (V) is found to be

$$V = c_1 e^{4kt} \ . \tag{37}$$

The directional Hubble parameters inthe directions of x, y, z and ψ axes respectively are

$$H_x = H_y = H_z = \left(k + \frac{1}{4\,c_3} e^{-4kt}\right) , \tag{38}$$

$$H_\psi = \left(k - \frac{3}{4\,c_3} e^{-4kt}\right). \tag{39}$$

The mean Hubble parameter (H) is obtained as

$$H = k\,. \tag{40}$$

The anisotropic parameter (Δ) of the expansionis found to be

$$\Delta = \frac{3}{16\,k^2 c_3^2} e^{-8kt} , \tag{41}$$

The expansion scalar (θ) is found to be

$$\theta = 4k\,. \tag{42}$$

The Shear scalar (σ^2) is found to be

$$\sigma^2 = \frac{3}{8\,c_3^2} e^{-8kt}\,. \tag{43}$$

Using equations (35) and (36) in equation (16) with the help of linear equation of state (10) for $\varepsilon = \frac{1}{3}$, we obtain the energy density and pressure of the quark matter as

$$\rho_q = \frac{9\,(3c_3 - 1)}{16\,c_3^2\,(24\pi + 7\lambda)} e^{-8kt} - \left[\frac{18k^2 + 3(8\,\pi + 5\lambda)B_c}{(24\,\pi + 7\lambda)}\right] , \tag{44}$$

$$p_q = \frac{3\,(3c_3 - 1)}{16\,c_3^2\,(24\pi + 7\lambda)} e^{-8kt} - \left[\frac{6k^2 + (8\,\pi + 5\lambda)B_c}{(24\,\pi + 7\lambda)}\right] . \tag{45}$$

Similarly, using equations (35) and (36) in equation (16) with the help of linear equation of state (12), we obtain the energy density and pressure of the strange quark matter as

$$\rho = \frac{9\,(3c_3 - 1)}{16\,c_3^2\,(24\pi + 7\lambda)} e^{-8kt} - \left[\frac{18k^2 + (24\,\pi + 23\lambda)B_c}{(24\,\pi + 7\lambda)}\right] . \tag{46}$$

$$p = \frac{3\,(3c_3 - 1)}{16\,c_3^2\,(24\pi + 7\lambda)} e^{-8kt} - \left[\frac{6k^2 + (40\,\pi + 17\lambda)B_c}{(24\,\pi + 7\lambda)}\right]. \tag{47}$$

Discussion and Conclusion:-

In this paper, the Kaluza-Klein cosmological model with quark and strange quark matters in $f(R,T)$ theory of gravity has been studied. The general solutions of the field equations of Kaluza-Klein space-time have been obtained under the assumption of constant deceleration parameter in the context of exponential volumetric expansion model.

Equations (35) and (36) gives the solution of Kaluza-Klein cosmological model for exponential volumetric expansion in $f(R,T)$ gravity. From equations (35) and (36), it is observed that as $t \to 0$, $A(t) \to \left(\frac{c_1}{c_4}\right)^{1/4} e^{(1/16k\,c_3)}$, $B(t) \to (c_1 c_4^3)^{1/4}\, e^{(3/16k\,c_3)}$ and as $t \to \infty$, $A(t) \to \infty$, $B(t) \to \infty$.

In Exponential Volumetric Expansion Model, it is observed that the spatial volume V is finite at $t = 0$, expands exponentially as t increases and become infinitely large as $t \to \infty$ as shown in figure-1.

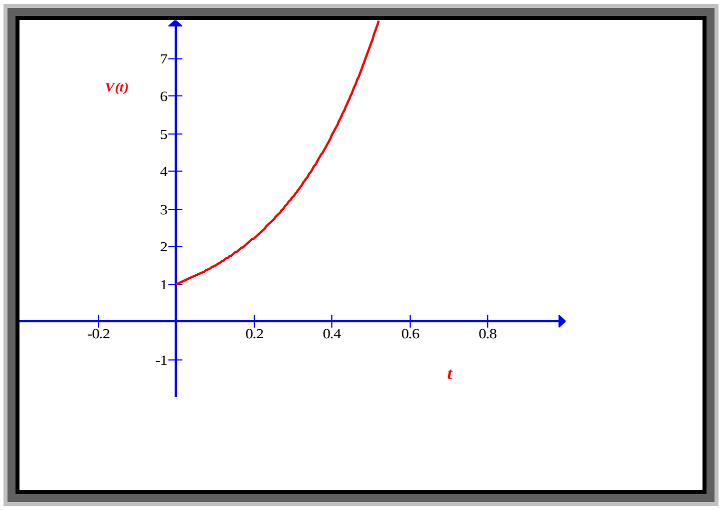

Figure 1:- Spatial volume $V(t)$ against cosmic t for $c_1 = 1,\ k = 1$.

From equations (38) and (39), it is observed that the directional Hubble parameters $H_x,\ H_y\ and\ H_z$ are finite at $t = 0$ and $t = \infty$. The mean Hubble parameter (H), the expansion scalar (θ) are constant for all values of t. Thus, the model represents uniform expansion.

The anisotropy of the expansion (Δ) is not promoted by the anisotropy of the fluid. Here the anisotropy of the expansion $\Delta \to constant$ as $t \to 0$ and then decreases to null exponentially as t increases provided that $k = c_3 = 1$. The space approaches to isotropy in this model since $\Delta \to 0$ as $t \to \infty$ as shown in figure-2.

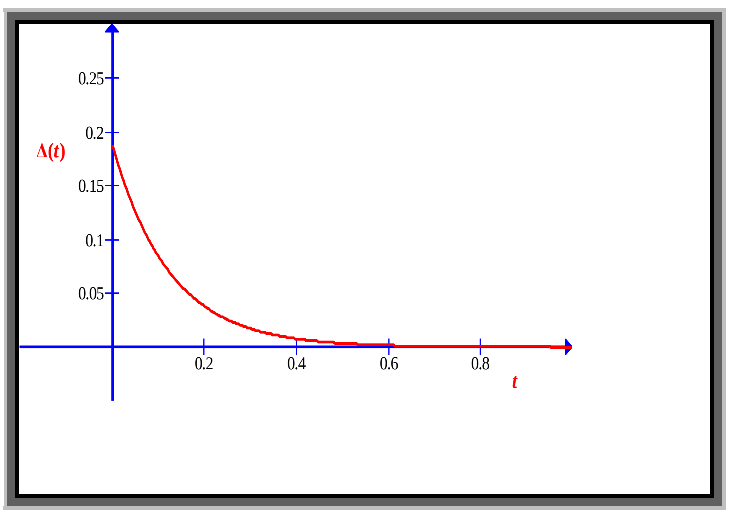

Figure 2:- Variation of anisotropic parameter (Δ) against cosmic time t for $k = 1\ , c_3 = 1$.

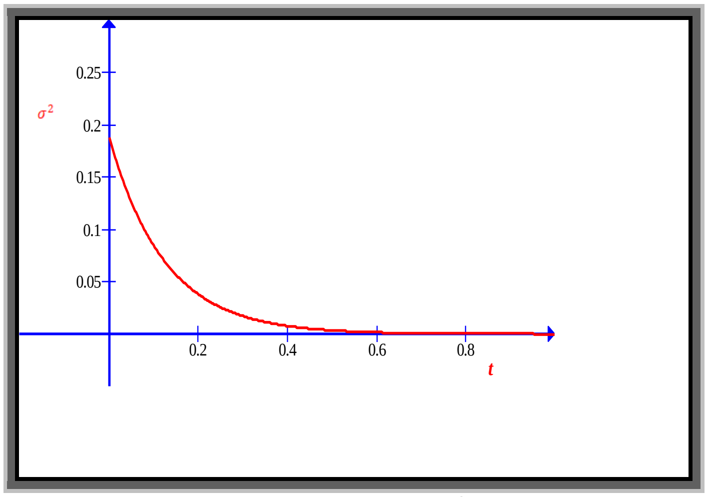

Figure 3:- The variation of Shear scalar (σ^2) against cosmic time t for $k = 1$, $c_3 = 1$.

From equation (4.19), it is observed that the shear scalar (σ^2) start with finite value at $t = 0$ and as time increases it decreases then tends to zero at $t \to \infty$ as shown in figure-3.

The ratio $\frac{\sigma^2}{\theta^2} = \left(\frac{3}{128\,k^2 c_3^2}\right)\frac{1}{e^{8kt}} \to 0$ as $t \to \infty$. Hence the model isotropizes for large value of t.

From equations (4.20) to (4.23), one can observed that density and pressure of quark matter (including strange quark models) become constants when as $t \to 0$ and then decreases exponentially as t increases and remain constant through out the evolution and hence there is no big bang type of singularity.

From equation (31), it is observed that the present model for $m = 0$ ($q = -1$) with negative deceleration parameter indicating that the universe is accelerating which is consistent with the present-day observations. For this model, we get $q = -1$ which implies the fastest rate of expansion of the universe. Riess *et al.*[1, 40] and Perlmutter *et al.*[2] have shown that the deceleration parameter of the universe is in the range $-1 \leq q \leq 0$ and the present-day universe is undergoing accelerated expansion.

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