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Accelerating Holographic Dark Energy cosmological model in modified gravity

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Abstract:

A class of solutions of field equations in $f(R,T)$ gravity proposed by Harko et. al. (2011) for Plane Symmetric Riemannian space-time with dark matter and Holographic Dark Energy (HDE) is talked about. Exact solutions of field equations are obtained with a special form of deceleration parameter. The negative value of the deceleration parameter represents the present acceleration of the universe. It is observed that EoS parameter converges to the negative value i.e. cosmological constant. The physical and geometrical parameters of the models are discussed in detail.

Keywords: Modified gravity, HDE, Plane symmetric.

Introductio

Our universe is accelerating and expanding as designated by observational data [1-3]. The modified theories of gravity are appealing numerous relativists to explore the growth and speeding up of the universe. In recent times, numerous cosmologists and astrophysicists have considered $f(R,T)$ theory. In $f(R,T)$ theory [4], the gravitational Lagrangian is specified by an arbitrary function of the Ricci scalar R and the trace T of the stress energy tensor. Houndjo [5] discussed the transaction of matter dominated point to an acceleration era.

Several cosmologists [6-24] have investigated the cosmological models in $f(R, T)$ gravity in different context.

Cosmological varieties of HDE as a developing model are explored on the basis of holographic principle [25-34]. Sharif and Jawad[35] studied interacting modified HDE in the Kaluza-Klein universe . Samanta [36] premeditated HDE cosmological model within the existence of quintessence. HDE cosmological models are examined in Refs.[37-48].The main aim of the present work is to study the Plane symmetric cosmological model in the presence of matter and holographic Ricci dark energy in the frame work of $f(R,T)$ gravity .

2. Metric, Energy Momentum Tensor and Field Equations

The $f(R,T)$ theory of gravity is the modification of General Relativity (GR). The field equations of $f(R,T)$ gravity obtained from the action

$S=\frac{1}{16\pi G}\int\sqrt{-g}\ f(R,T)\,d^4x+\int\sqrt{-g}\ L_m d^4x$, where $f(R,T)$ is an arbitrary function of the Ricci scalar (R) and trace of the stress energy tensor (T) of the matter T_{ij} $(T=g^{ij}T_{ij})$ and L_m is the matter Lagrangian density. The field equations in $f(R,T)$ theory of gravity for the function $f(R,T)=R+2f(T)$ when the matter source is perfect fluid and given by

$$R_{ij}-\frac{1}{2}Rg_{ij}=8\pi T_{ij}+2f'(T)T_{ij}+[2pf'(T)+f(T)]g_{ij}.$$

Here prime denotes differentiation with respect to the argument, $f(T)$ is an arbitrary function of the trace of stress energy tensor of matter and p is the pressure of the matter source, which is a perfect fluid. Consider a Plane Symmetric Riemannian space-time described by the line element

$$ds^2=e^{2h}\left(dt^2-dr^2-r^2d\theta^2-s^2dz^2\right), \tag{1}$$

where r, θ, z are the usual cylindrical polar coordinates and h and s are functions of t alone. The energy momentum tensor for matter and holographic dark energy are defined as

$$T_{\mu\nu}=\rho_m u_\mu u_\nu\,;\ \overline{T}_{\mu\nu}=(\rho_\lambda+p_\lambda)u_\mu u_\nu+g_{\mu\nu}p_\lambda, \tag{2}$$

where ρ_m is the energy densities of matter, ρ_Λ is the holographic dark energy and p_Λ is the pressure of the holographic dark energy. The holographic dark energy density is given by $\rho_\lambda=3(\alpha_1 H^2+\beta_1\dot{H})$, with $M_p^{-2}=8\pi G=1.$ The continuity equation can be obtained as

$\dot{\rho}_m+\dot{\rho}_\lambda+3H(\rho_m+\rho_\lambda+p_\lambda)=0.$ The continuity equation of the matter is $\dot{\rho}_m+3H\rho_m=0.$

The continuity equation of the holographic dark energy is $\dot{\rho}_\lambda+3H(\rho_\lambda+p_\lambda)=0.$ The barotropic equation of state is $p_\lambda=\omega_\lambda\rho_\lambda.$ The EoS HDE parameter is obtained as

$$\omega_\lambda=-1-\frac{2\alpha_1 H\dot{H}+\beta_1\ddot{H}}{3H(\alpha_1 H^2+\beta_1\dot{H})}. \tag{3}$$

Now we choose the function $f(T)$ as the trace of the stress energy tensor of the matter so that, $f(T)=\mu T$,where μ is an arbitrary constant.

With the help of equations (1) and (2), the field equation can be written as

$$e^{-2h}\left(2\ddot{h}+\dot{h}^2+\frac{2\dot{h}\,\dot{s}}{s}+\frac{\ddot{s}}{s}\right)=8\pi p_\lambda-\left[-3p_\lambda+\rho_m+\rho_\lambda\right]\mu, \quad (4)$$

$$e^{-2h}\left(2\ddot{h}+\dot{h}^2\right)=8\pi p_\lambda-\left[-3p_\lambda+\rho_m+\rho_\lambda\right]\mu, \quad (5)$$

$$e^{-2h}\left(\frac{2\dot{h}\dot{s}}{s}+3\dot{h}^2\right)=-8\pi\left(\rho_m+\rho_\lambda\right)-\left[-p_\lambda+3\rho_m+3\rho_\lambda\right]\mu. \quad (6)$$

Here the overhead dot denotes differentiation with respect to *t*.

3.Solution of field equations

The Einstein field equations are a coupled system of highly non-linear system of differential equations and we seek physical solutions to the field equations for applications in cosmology and astrophysics. There are only three independent equations with five unknowns $h, s, \rho_\lambda, \rho_m, p_\lambda$. The solution of the field equations are generated by applying a special form of deceleration parameter with two more conditions as,

i) we assume the relation between the metric potentials such as

$$e^h=\beta s^n, \quad (7)$$

where $\beta\neq 0,\ n>1$ are the constants.

Cunha and Lima [49] favors recent acceleration and past deceleration with high degree of statistical confidence level by analyzing three SNe-Ia data. In order to match this observation, Singh and Debnath [50] has defined a special form of deceleration parameter for FRW metric as

$$q=-\frac{\ddot{a}a}{\dot{a}^2}=-1+\frac{\alpha}{1+a^\alpha}, \quad (8)$$

where $\alpha>0$ is a constant and *a* be the scale factor of the Universe.

As the sign of q indicates whether the model inflates or not. A positive sign of q, i.e., $q>0$, correspond to a "standard" decelerating model, whereas a negative sign of i.e. $q<0$, indicates inflation. It is remarkable to mention here that al-though the current observations of SNe-Ia and CMBR favor accelerating models, i.e., $q<0$ but both do not altogether.

Solving equation (8) one can obtain the Hubble's parameter as

$$H = \frac{\dot{a}}{a} = k(1 + a^{-\alpha}), \tag{9}$$

where k is a constant of integration which on integration comes out

$$a = \left(e^{\alpha kt} - 1\right)^{\frac{1}{\alpha}}. \tag{10}$$

Using equations (7) and (10), we obtain

$$s = \left(\frac{1}{r\beta^4}\right)^{\frac{1}{4n+1}} \left(e^{\alpha kt} - 1\right)^{\frac{3}{\alpha(4n+1)}}, \tag{11}$$

$$e^h = \beta\left(\frac{1}{r\beta^4}\right)^{\frac{n}{(4n+1)}} \left(e^{\alpha kt} - 1\right)^{\frac{3n}{\alpha(4n+1)}}. \tag{12}$$

With the suitable choice of coordinates and constants, the metric (1) with the help of equations (11) and (12) becomes

$$ds^2 = \beta^2\left(\frac{1}{r\beta^4}\right)^{\frac{2n}{(4n+1)}} \left(e^{\alpha kt} - 1\right)^{\frac{6n}{\alpha(4n+1)}} \left\{ \begin{array}{l} dt^2 - dr^2 - r^2 d\theta^2 - \\ \left(\frac{1}{r\beta^4}\right)^{\frac{2}{(4n+1)}} \left(e^{\alpha kt} - 1\right)^{\frac{6}{\alpha(4n+1)}} dz^2 \end{array} \right\}. \tag{13}$$

4. Kinematical properties

Equation (13) represents non-static plane symmetric HDE model in $f(R,T)$ gravity with the following physical and kinematical parameters of the model which are important for discussing the physical behavior of the model. The spatial volume $V = \left(e^{\alpha kt} - 1\right)^{\frac{3}{\alpha}}$.It is observed that the volume vanishes at initial time $t = 0$ and approaches to infinite at time $t = \infty$ i.e. expands exponentially (see Fig 1). The expansion scalar $\theta = \frac{3ke^{\alpha kt}}{\left(e^{\alpha kt} - 1\right)}$. The Hubble parameter $H = \frac{ke^{\alpha kt}}{\left(e^{\alpha kt} - 1\right)}$.The deceleration parameter, Shear scalar and anisotropic parameter are obtained as $q = \frac{\alpha}{e^{\alpha kt}} - 1, \sigma^2 = \frac{k^2(4n^2 - 12n + 13)}{(4n+1)}\left(\frac{e^{\alpha kt}}{e^{\alpha kt} - 1}\right)$ and $A_m = \frac{2}{3}\frac{(4n^2 - 12n + 13)}{(4n+1)}$. The expansion scalar, the Hubble parameter, shear scalar and mean anisotropy parameter are constant throughout the evolution of the Universe as $t \to \infty$. This shows that the Universe is expanding with the increase of cosmic time but the rate of expansion decrease to constant value. Also, $\frac{\sigma^2}{\theta^2} \neq 0$, and hence the model does not approach isotropy for large values of t.

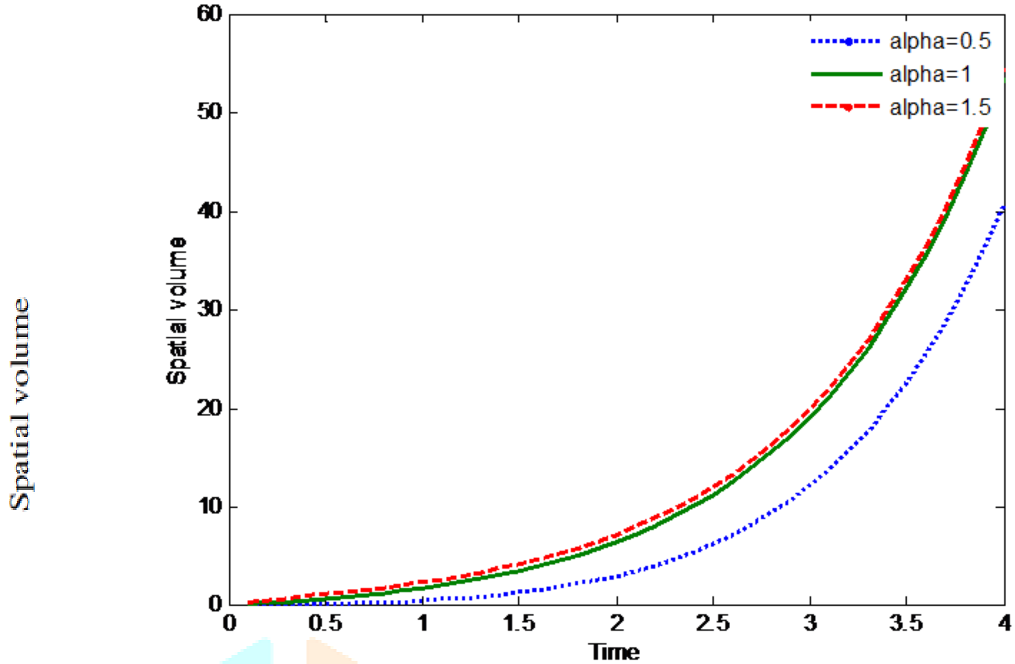

Figure 1**:** Spatial volume versus time .

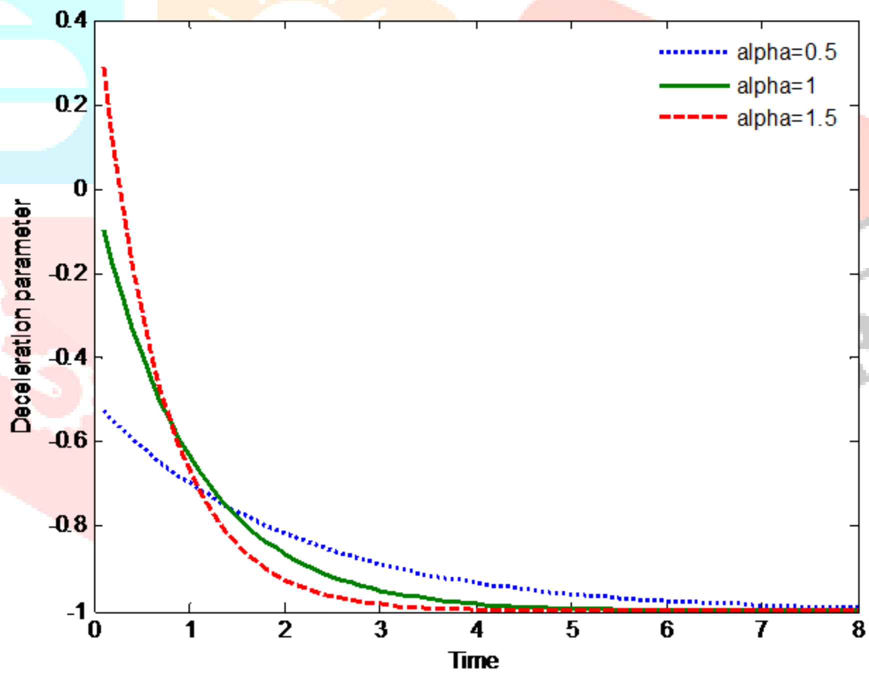

Figure 2**:** Deceleration parameter versus time .

From fig 2, it is observed that accelerated expansion of the model depends on the value of α. Initially for some small interval of time ($\alpha \geq 1$), the Universe shows decelerating expansion while for $\alpha < 1$, it always shows accelerated expansion (see fig 2).

5. Physical properties

The energy density of Holographic Dark Energy is given by

$$\rho_\lambda = 3\left\{\frac{\alpha_1 k^2 e^{2\alpha kt}}{\left(e^{\alpha kt}-1\right)^2} - \frac{\beta_1 \alpha k}{\left(e^{\alpha kt}-1\right)}\right\}. \tag{14}$$

The energy density of matter is obtained as

$$\rho_m = \left(e^{\alpha kt}-1\right)^{\frac{-3}{\alpha}}. \tag{15}$$

The EoS parameter is found out to be

$$\omega_\lambda = -1 - \frac{\alpha_1 \frac{k e^{\alpha kt}}{\left(e^{\alpha kt}-1\right)}\left\{\frac{-\alpha k}{\left(e^{\alpha kt}-1\right)}\right\} + \beta_1 \frac{\alpha^2 k^2 e^{2\alpha kt}}{\left(e^{\alpha kt}-1\right)^3}}{3\frac{k e^{\alpha kt}}{\left(e^{\alpha kt}-1\right)}\left\{\frac{\alpha_1 k^2 e^{2\alpha kt}}{\left(e^{\alpha kt}-1\right)^2} - \frac{\beta_1 \alpha k}{\left(e^{\alpha kt}-1\right)}\right\}}. \tag{16}$$

The anisotropic pressure yields

$$p_\lambda = \left[-1 - \frac{\alpha_1 \frac{k e^{\alpha kt}}{\left(e^{\alpha kt}-1\right)}\left\{\frac{-\alpha k}{\left(e^{\alpha kt}-1\right)}\right\} + \beta_1 \frac{\alpha^2 k^2 e^{2\alpha kt}}{\left(e^{\alpha kt}-1\right)^3}}{3\frac{k e^{\alpha kt}}{\left(e^{\alpha kt}-1\right)}\left\{\frac{\alpha_1 k^2 e^{2\alpha kt}}{\left(e^{\alpha kt}-1\right)^2} - \frac{\beta_1 \alpha k}{\left(e^{\alpha kt}-1\right)}\right\}}\right]\left[3\left\{\frac{\alpha_1 k^2 e^{2\alpha kt}}{\left(e^{\alpha kt}-1\right)^2} - \frac{\beta_1 \alpha k}{\left(e^{\alpha kt}-1\right)}\right\}\right]. \tag{17}$$

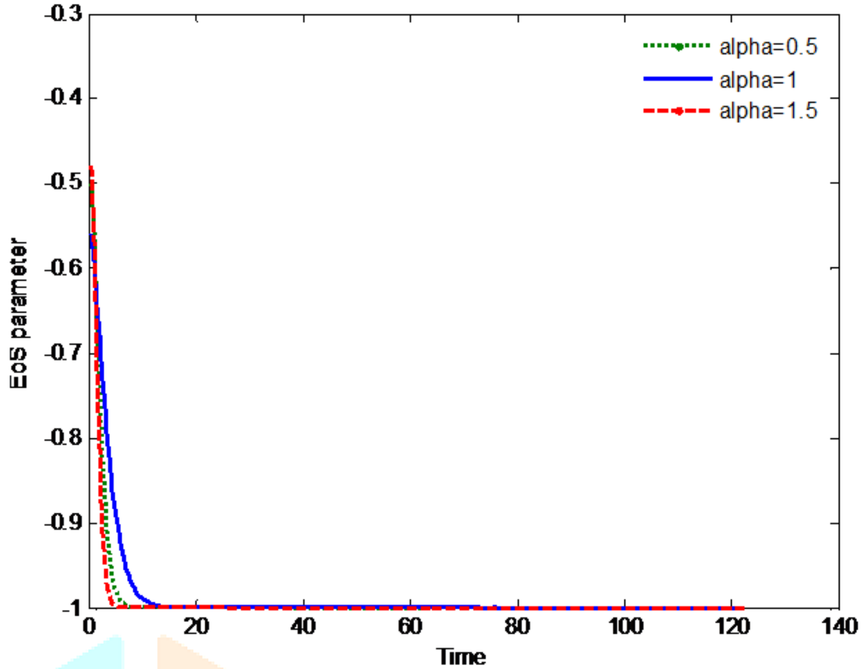

Figure 3**:** EoS parameter versus time .

It may be observed that the cosmological model in $f(R,T)$ gravity has initial singularity i.e. at $t=0$. The energy density tends to zero as $t\rightarrow\infty$. A large class of scalar field DE models has been studied including Quintessence $(\omega_{\lambda}>-1)$, Phantom$(\omega_{\lambda}<-1)$ and Quinton (which can cross from the region to the Quintessence region). The Quinton scenario of DE is designed to understand the nature of DE with ω_{λ} cross (-1). In the derived model, the EoS parameter is evolving with a negative sign, which may be established from the current accelerated expansion of the Universe. From Fig. 3 we observed that at the initial time there is a quintessence $(\omega_{\lambda}>-1)$ region, and at late time it approaches the cosmological constant $(\omega_{\lambda}=-1)$ scenario. This is a situation in the early Universe where the quintessence-dominated Universe may be playing an important role for the EoS parameter.

6. Conclusion

It is well known that anisotropic DE models with variable EoS parameter in modified theories of gravity play a vital role in the discussion of the accelerated expansion of the Universe which is the crux of the problem in the present scenario. In this manuscript, we have investigated non-static plane symmetric DE model in $f(R,T)$ gravity with variable EoS parameter in the presence of holographic dark energy source. It is observed that the expansion scalar is infinite at t = 0, but as cosmic time increases it decreases and stops at a finite value after some time t. For $\alpha\geq1$ the model sometimes decelerate in a standard way and later accelerate which is in accordance with the present scenario.It is observed that EoS parameter, energy density in the model is all functions of time. It can also be seen that the model is accelerating, expanding and has initial singularity. If the present model is compared with the experimental results, one can conclude that the limit of ω_λ may be accumulated with the acceptable range of EoS parameters. This model confirms the SNe-Ia supernova experiment (see fig.3).

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