АСТРОФИЗИКА

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DARK ENERGY COSMOLOGICAL MODEL IN A MODIFIED THEORY OF GRAVITY

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The dark energy model with Equation of State (EoS) parameter are derived for non-static plane symmetric space-time filled with perfect fluid source in the frame work of $f(R, T)$ gravity (Harko et al., arXiv: 1104.2669v2 [gr-qc], 2011). To obtain a determinate solution special form of deceleration parameter (DP) is used. We have assumed that the relation between metric potentials and the EoS parameter is proportional to skewness parameter. It is observed that the EoS parameter, skewness parameters in the model turn out to be functions of cosmic time. Some physical and kinematical properties of the model are also discussed.

Key words: *Non-static plane symmetric metric:* $f(R, T)$ *gravity: Dark Energy*

1. *Introduction.* Recent cosmological observations from supernova [1-5], WMAP [6-9], Oscillation data [10] predicted that the present universe is passing through a phase of accelerating expansion which might have fuelled due to existence of a new source called dark energy (DE). The dynamical dark energy models are classified in two different categories: (i) the scalar fields including quintessence [11, 12], phantom [13-19], quintom [20-22], K-essence [23-25], tachyon [26-28], dilaton [29-31] and so forth. (ii) The interacting models of dark energy such as chaplygin gas models [32-34], braneworld models [35,36], holographic [37-45] and agegraphic [46,47] model. Along with, Ray et al. [48] investigated variable equation of state for generalized dark energy model. Yadav and Yadav [49] has obtained Bianchi type-II anisotropic dark energy model with constant deceleration parameter. Recently, Pradhan and Amirhashchi [50] have investigated a new anisotropic Bianchi type-III dark energy model in general relativity with equation of state (EoS) parameter without assuming constant deceleration parameter. Saha and Yadav [51] presented a spatially homogeneous and anisotropic LRS Bianchi type-II dark energy model in general relativity. They have obtained exact solutions of Einstein's field equations which for some suitable choices of problem parameters yield time dependent EoS and DP parameters, representing a model which generates a transition of universe from early decelerating phase to present accelerating phase. They have also studied DE models with variable EoS parameter (Yadav and Saha, [52]).

Nojiri & Odintsov [53] described the reasons why modified gravity approach is extremely attractive in the applications for late accelerating universe and Dark Energy. Another good review on modified gravity was made by Clifton et al. [54]. Many different theories of modified gravity have been recently proposed: some of them are $f(R)$ (with R being the Ricci scalar curvature) [55,56], $f(T)$ (with T being the torsion scalar) [57-60], Horava-Lifshitz [61,62] and Gauss-Bonnet [63-66] theories. Harko et al [67] recently suggested an extension of standard General Relativity, where the gravitational Lagrangian is given by an arbitrary function of R and T and called this model as $f(R,T)$. The $f(R,T)$ model depends on a source term, representing the variation of the matter stress-energy tensor with respect to the metric. A general expression for this source term can be obtained as a function of the matter Lagrangian L_m.

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

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

where $f(R,T)$ is an arbitrary function of the Ricci scalar R and the trace T of the stress energy tensor of matter and L_m be the matter Lagrangian.

The stress energy tensor of matter is

$$T_{ij}=-\frac{2}{\sqrt{-g}}\frac{\partial\left(\sqrt{-g}\right)}{\partial g^{ij}}L_m, \quad \Theta_{ij}=-2T_{ij}-pg_{ij}, \tag{2}$$

Using gravitational units (by taking G & c as unity) the corresponding field equations of $f(R,T)$ gravity are obtained by varying the action principle (1) with respect to g_{ij} as

$$\begin{aligned} f_R(R,T)R_{ij}-\frac{1}{2}f(R,T)g_{ij}+f_R(R,T)\times\left(g_{ij}\nabla^i\nabla_i-\nabla_i\nabla_j\right)= \\ =8\pi T_{ij}-f_T(R,T)T_{ij}-f_T(R,T)\Theta_{ij} \end{aligned} \tag{3}$$

where $f_R=\frac{\delta f(R,T)}{\delta R}$, $f_T=\frac{\delta f(R,T)}{\delta T}$ and $\Theta_{ij}=g^{\alpha\beta}\frac{\delta T_{\alpha\beta}}{\delta g^{ij}}$.

Here ∇_i is the covariant derivative and T_{ij} is usual matter energy-momentum tensor derived from the Lagrangian L_m. It can be observed that when $f(R,T)=f(R)$ then equation (3) reduce to field equations of $f(R)$ gravity.

It is mentioned here that these field equations depend on the physical nature of the matter field. Many theoretical models corresponding to different matter contributions for $f(R,T)$ gravity are possible. However, Harko et al. [67] gave three classes of these models

$$f(R,T)=\begin{cases} R+2f(T) \\ f_1(R)+f_2(T) \\ f_1(R)+f_2(R)f_3(T) \end{cases}$$

In this paper we are focused to the first class, i.e.

$$f(R,T)=R+2f(T), \tag{4}$$

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

Paul et al. [68] obtained FRW models in $f(R)$ gravity while Sharif and Shamir [69,70] have studied the solutions of Bianchi type-I and V space-times in the framework of $f(R)$ gravity. Sheykhi [71] has discussed magnetic strings in $f(R)$ gravity and Yilmaz et al. [72] have discussed quark and strange quark matter in $f(R)$ gravity for Bianchi type I and V space-times. Adhav [73] has obtained Bianchi type-I cosmological model in $f(R,T)$ gravity. Reddy et al. [74,75] have discussed Bianchi type-III and Kaluza-Klein cosmological models in $f(R,T)$ gravity while Reddy and Shantikumar [76] studied some anisotropic cosmological models and Bianchi type-III dark energy model, respectively, in $f(R,T)$ gravity. Chaubey and Shukla [77] have obtained a new class of Bianchi cosmological models in $f(R,T)$ gravity. Katore and Shaikh investigate [78,79] Kantowaski-Sachs and Bianchi type II, VIII & IX Cosmological Models with anisotropic dark energy in $f(R,T)$ gravity. Rao et al. [80] have obtained LRS Bianchi type-I with perfect fluid in a modified theory of gravity. Recently Rao and Neelima [81,82] have discussed perfect fluid Einstein-Rosen and Bianchi type-V_{I0} universes in $f(R,T)$ gravity respectively.

Moreover, in recent years Bianchi universes have been gaining an increasing interest of observational cosmology, since the WMAP data seem to require an addition to the standard cosmological model with positive cosmological constant that resembles the Bianchi morphology. According to this, the universe should achieved a slightly anisotropic special geometry in spite of the inflation, contrary to generic inflationary models and that might be indicating a non-trivial isotropization history of universe due to the presence of an anisotropic energy source. In principle, once the metric is generalized to Bianchi types, the EoS parameter of the fluid can also be generalized in a way conveniently to wield anisotropy with the considered metric. In such models, where both the metric and EoS parameter of the fluid are allowed exhibiting an anisotropic character, the universe can exhibit non-trivial isotropization histories and it can be examined whether the metric and/or the EoS parameter of fluid evolve toward isotropy. Thus, the Bianchi models which remain anisotropic are of rather academical interest.

The theory of an inhomogeneous anisotropic universe has two main directions, which are characterized as follows: a) the search for exact particular solutions of the equations of gravitation, and the consideration of such models which bear the properties of symmetry; b) as common as possible, the qualitative study of the behavior (evolution) of matter and the metric under different physical assumptions. The models, which are spherically symmetric under the vanishing of the pressure, viscosity, and the flow of energy, the models with a spherically symmetric distribution of matter concentrated in a centre (core).

The universe is spherically symmetric and the matter distribution is isotropic and homogeneous. But during the early stages of evaluation, it is unlikely that it could have had such a smoothed out picture. Hence we consider plane symmetric which provides an opportunity for the study of inhomogeneity.

Motivated by the above discussion, the dark energy model with EoS parameter are derived for non-static plane symmetric space-time filled with perfect fluid source in the frame work of $f(R,T)$ gravity, where $f(R,T)=R+2f(T)$. This model is very important in the discussion of large scale structure, to identify early stages and finally to study the evolution of the universe.

2. *Metric, Energy Momentum Tensor and Field Equations.* We consider a Riemannian space-time described by the line element

$$ds^2 = e^{2h}\left(dt^2 - dr^2 - r^2\, d\theta^2 - s^2\, dz^2\right), \tag{5}$$

where r, θ, z are the usual cylindrical polar coordinates and h & s are functions of t alone. It is well known that this line element is plane symmetric.

From equations (3) and (4), we get the gravitational field equations as

$$G_{ij} = R_{ij} - \frac{1}{2}Rg_{ij} = 8\pi T_{ij} - 2f'(T)T_{ij} - 2f'(T)\Theta_{ij} + f(T)g_{ij}, \tag{6}$$

where the overhead prime indicates differentiation with respect to the argument.

The Energy momentum tensor for anisotropic dark energy is given by

$$\begin{aligned} T^i_j &= \mathrm{diag}\left[\rho, -p_x, -p_y, -p_z\right] \\ &= \mathrm{diag}\left[1, -w_x, -w_y, -w_z\right], \end{aligned} \tag{7}$$

where ρ is the energy density of the fluid and p_x, p_y, p_z are the pressure along x, y, z axes respectively.

The Energy momentum tensor can be parameterized as

$$T^i_j = \mathrm{diag}\left[1, -(w+\delta), -(w+\delta), -w\right]\rho. \tag{8}$$

For the sake of simplicity we choose $w_x = w$ and the skewness parameter δ are the deviations from w on x and y axes respectively. Then the field equations (6) can be written as

$$R^i_j - \frac{1}{2}R\delta^i_j = 8\pi T^i_j - 2f'(T)T + \left[2pf(T) + f(T)\right]\delta^i_j. \tag{9}$$

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.

Now with the help of equation (3), the field equations (9) for the metric (5) can be written as

$$e^{-2h}\left(2\ddot{h} + \dot{h}^2 + \frac{2\dot{h}\dot{s}}{s} + \frac{\ddot{s}}{s}\right) = (8\pi + 2\mu)(\omega + \delta)\rho - \mu(1 - 3\omega - 2\delta)\rho - 2\mu p, \tag{10}$$

$$e^{-2h}\left(2\ddot{h}+\dot{h}^2\right)=8\pi(\omega)\rho-\mu(1-3\omega-2\delta)\rho-2\mu p, \tag{11}$$

$$e^{-2h}\left(\frac{2\dot{h}\dot{s}}{s}+3\dot{h}^2\right)=-(8\pi+2\mu)\rho-\mu(1-3\omega-2\delta)-2\mu p. \tag{12}$$

Here the over head dot denotes differentiation with respect to t.

The spatial volume V and the generalized Hubble's parameter H for the space-time (5) are defined by

$$V = rse^{4h}, \tag{13}$$

$$H = \frac{\dot{a}}{a}. \tag{14}$$

The physical quantities of observational interest in cosmology such as the expansion θ, the anisotropy parameter A_m, and the shear scalar σ^2 defined as follows

$$\theta = 3H, \tag{15}$$

$$A_m = \frac{1}{3}\sum_{i=1}^{3}\left(\frac{\Delta H_i}{H}\right)^2, \tag{16}$$

$$\sigma^2 = \frac{3}{2}A_m H^2. \tag{17}$$

3. *Solutions of Field Equations.* The Einstein's field equations (10) to (12) are a coupled system of 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, ρ, ω, δ. The Solution of field equations generated by applying law of variation of Hubble's parameter which was first proposed by Berman [5] in FRW-model that yield a constant value of deceleration parameter. Hence to find deterministic solution two more conditions are necessary, we consider the following conditions,

(i) we assume the relation between the metric potentials which is given as follows

$$e^h = \beta s^n, \tag{18}$$

where β is constant and $n > 1$.

(ii) The E0S parameter w is proportional to skewness parameter δ such that

$$w + \delta = 0. \tag{19}$$

Recently, Cunha and Lima [83] favors recent acceleration and past deceleration with high degree of statistical confidence level by analyzing three SNe type Ia samples. In order to match this observation, Singh and Debnath [84] has defined a special form of deceleration parameter for FRW metric as

$$q=-\frac{\ddot{a}a}{\dot{a}^2}=-1+\frac{\alpha}{1+a^{\alpha}}, \tag{20}$$

where $\alpha>0$ is a constant and a is mean scale factor of the universe.

We observe that the relation (20) gives q as a constant. The sign of q indicated whether the model inflates or not. The positive sign of q i.e. $q>0$ correspond to "standard" decelerating model whereas the negative sign of q i.e. $q<0$ indicates inflation. It is remarkable to mention here that though the current observations of SNe Ia and CMBR (Cosmic Microwave Background Radiation) favors accelerating models i.e. $q<0$, but both do not altogether.

After solving (20) one can obtain the mean Hubble parameter H as

$$H=\frac{\dot{a}}{a}=k\left(1+a^{-\alpha}\right), \tag{21}$$

where k is a constant of integration.

On integrating (21), we obtain the mean scale factor as

$$a=\left(e^{\alpha kt}-1\right)^{1/\alpha}. \tag{22}$$

Using equations (13), (18) and (22), we obtain

$$s=\left(\frac{1}{r\beta^4}\right)^{\frac{1}{4n+1}}\left(e^{\alpha kt}-1\right)^{\frac{3}{\alpha(4n+1)}}, \tag{23}$$

$$e^h=\beta\left(\frac{1}{r\beta^4}\right)^{\frac{n}{(4n+1)}}\left(e^{\alpha kt}-1\right)^{\frac{3n}{\alpha(4n+1)}}. \tag{24}$$

With the suitable choice of coordinates and constants, the metric (5) with the help of equations (23) and (24) becomes

$$ds^2=\beta^2\left(\frac{1}{r\beta^4}\right)^{\frac{2n}{(4n+1)}}\left(e^{\alpha kt}-1\right)^{\frac{6n}{\alpha(4n+1)}}\times \\ \times\left\{dt^2-dr^2-r^2d\theta^2-\left(\frac{1}{r\beta^4}\right)^{\frac{2}{(4n+1)}}\left(e^{\alpha kt}-1\right)^{\frac{6}{\alpha(4n+1)}}dz^2\right\} \tag{25}$$

Equation (25) represents non-static plane symmetric dark energy Model in $f(R,T)$ theory of gravity

4. *Some properties of the model*. The physical and kinematical parameters of the model which are important for discussing the physical behavior of the model are:

The spatial volume of the universe is

$$V=\left(e^{\alpha kt}-1\right)^{1/\alpha}. \tag{26}$$

It is observed that the spatial volume vanishes at initial time $t=0$ and approaches to infinite at time $t\to\infty$ i.e. expand exponentially.

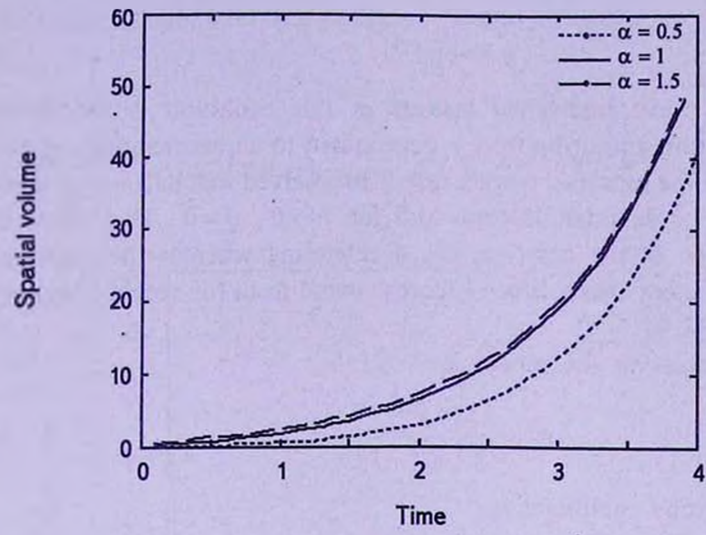

Fig.1. Behavior of Spatial volume of the universe versus time t.

The scalar expansion in the model is

$$\theta = \frac{3ke^{\alpha kt}}{\left(e^{\alpha kt}-1\right)}. \tag{27}$$

The generalized Hubble parameter is

$$H = \frac{ke^{\alpha kt}}{\left(e^{\alpha kt}-1\right)}. \tag{28}$$

The deceleration parameter is

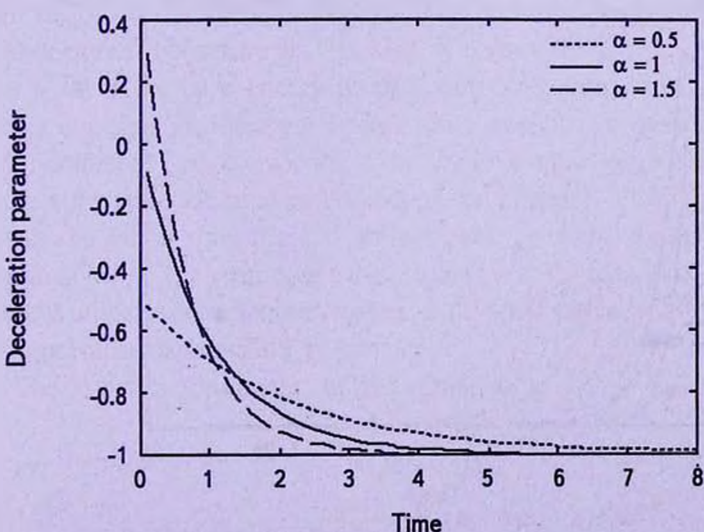

Fig.2. Behavior of deceleration parameter versus time t.

$$q = \frac{\alpha}{e^{\alpha kt}} - 1. \tag{29}$$

One of the most interesting aspects of this evolution is the recently established late-time transition from a decelerated to an accelerating regime of the expansion of the universe. In this case it is observed that as $t \to \infty$, $q \to -1$ this is the case of de-sitter universe and for $t \to 0$, $q = 0$. This shows that in the early stage of the universe was decelerating whereas the universe is accelerating at present epoch which is corroborated from the recent Supernovae Ia observations [2-4]

The shear scalar in the model is

$$\sigma^2 = \frac{3k}{2}\left(\frac{e^{\alpha kt}}{e^{\alpha kt} - 1}\right). \tag{30}$$

Mean anisotropy parameter is

$$A_m = \frac{\left(e^{\alpha kt} - 1\right)}{ke^{\alpha kt}}. \tag{31}$$

The expansion scalar, the generalized 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 which shows that the universe starts evolving with constant volume at $t \to \infty$ with an infinite rate of expansion. Also, $\sigma^2/\theta^2 \neq 0$, and hence the model does not approach isotropy for large values of *t*.

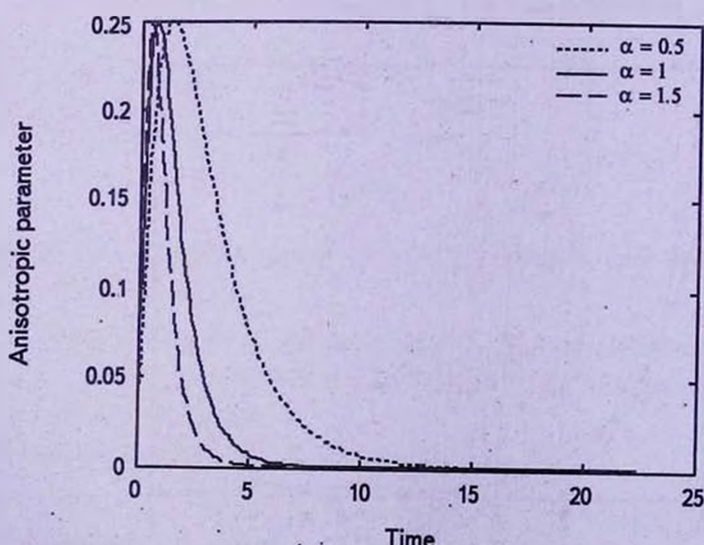

Fig.3. Behavior of anisotropy parameter versus time *t*.

The EoS parameter and skewness parameter in the model are

$$\omega = \frac{-1}{\rho(8\pi + 2\mu)} \times \left\{ \frac{3k^2 e^{\alpha kt}}{\beta^2} \left(r\beta^4\right)^{\frac{2n}{4n+1}} \left(e^{\alpha kt} - 1\right)^{\frac{-6n}{\alpha(4n+1)} - 2} \left[\frac{\left(3 - \alpha - 4n\alpha - 6n^2\right)e^{\alpha kt}}{(4n+1)^2} + \frac{\alpha\left(e^{\alpha kt} - 1\right)}{(4n+1)} \right] \right\}. \tag{32}$$

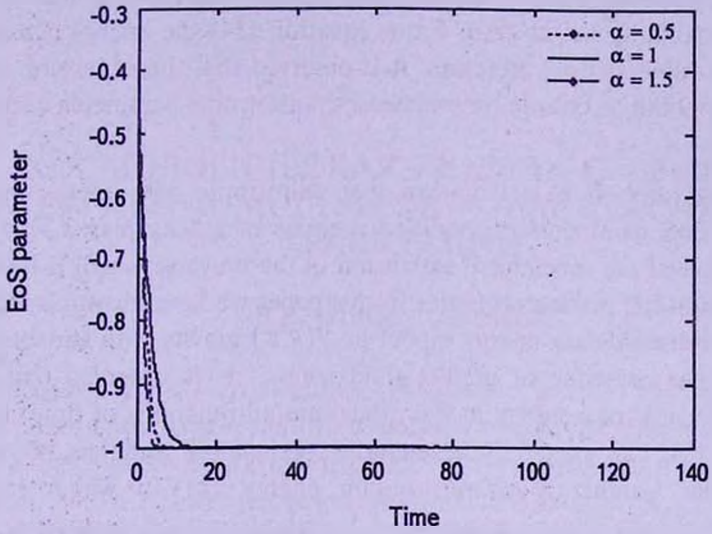

Fig.4. Behavior of EoS parameter versus time t.

A large class of scalar field DE models have been studied including quintessence ($\omega > -1$) [85], phantom ($\omega < -1$) [13] and quinton (that can cross from region to quintessence region). The quinton scenario of DE is designed to understand the nature of DE with ω cross (-1). Setare and Saridakis [86] have studied the dark energy models with EoS parameter across (-1) which gives a concrete justification for quinton paradigm. In the derived model, the EoS parameter (ω) is evolving with negative sign which may be established to the current accelerated expansion of the universe. From Fig.4 we observed that at the initial time there is quintessence ($\omega > -1$) region and at late time it approaches to the cosmological constant ($\omega = -1$) scenario. This is a situation in early universe where quintessence dominated universe [13] may be playing an important role for EoS parameter.

The skewness parameter of the model is

$$\delta = \frac{1}{\rho(8\pi + 2\mu)} \times \left\{ \frac{3k^2 e^{\alpha kt}}{\beta^2} \left(r\beta^4\right)^{\frac{2n}{4n+1}} \left(e^{\alpha kt} - 1\right)^{\frac{-6n}{\alpha(4n+1)} - 2} \left[\frac{\left(3 - \alpha - 4n\alpha - 6n^2\right)e^{\alpha kt}}{(4n+1)^2} + \frac{\alpha\left(e^{\alpha kt} - 1\right)}{(4n+1)} \right] \right\}. \tag{33}$$

The energy density in the model is

$$\rho = \frac{1}{(8\pi + 2\mu)} \times \left\{ \frac{3k^2 e^{\alpha kt}}{\beta^2} \left(r\beta^4\right)^{\frac{2n}{4n+1}} \left(e^{\alpha kt} - 1\right)^{\frac{-6n}{\alpha(4n+1)} - 2} \times \right.$$
$$\left. \times \left[\frac{\alpha\left(e^{\alpha kt} - 1\right) - 2n\alpha}{(4n+1)} + \frac{\left(3 - \alpha - 4n\alpha - 6n^2\right)e^{\alpha kt}}{(4n+1)^2} \right] \right\}. \tag{34}$$

It may be observed that the cosmological model in $f(R,T)$ gravity is free from initial singularity i.e. at $t=0$. From equation (34) the energy density ρ tends to finite value as time increases. It is observed that the expansion scalar is infinite at $t=0$ but as cosmic time increases, anisotropic parameter decreases as $t \to 0$ then $A_m \to 0$.

5. *Conclusions*. It is well known that anisotropic dark energy 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 paper we have investigated non-static plane symmetric dark energy model in $f(R,T)$ gravity with variable EoS parameter in the presence of perfect fluid source. It is observed that EoS parameter, skewness parameters in the model are all functions of time. It can also be seen that the model is accelerating, expanding and has no initial singularity. The Lorentz invariant vacuum energy (LIVE) which can be represented by a cosmological constant (Λ), with a constant equation of state parameter $\omega = -1$ (Fig.4), so called (ΛCDM) model, which in a flat universe model contains both LIVE and cold dark matter (CDM) i.e. dust, is the simplest cosmological model that is in agreement with current observation.

Some other limits of ω obtained from observational results that came from SNe Ia data [87] and a combination of SNe Ia data with CMB anisotropy and Galaxy clustering statistics [88,89] are $-1.67 < \omega < -0.62$ and $-1.33 < \omega < -0.79$ respectively. The latest result in 2009 obtain after the combination of cosmological datasets coming from CMB anisotropy, luminosity distances of high redshift SNe Ia and galaxy clustering constraint the dark energy EoS to $-1.44 < \omega < -0.92$ [90]. If the present model is compared with the experimental results mentioned above, one can conclude that the limit of ω provided by equation (32) may be accumulated with the acceptable range of EoS parameter. This model confirms the high redshift supernova experiment.

It is observed that the anisotropy increases as time increases and then decreases to zero after some time and remains zero after some finite times. Hence the model reaches to isotropy after some finite times which matches with the recent observations as the universe is isotropic at large scale also which resembles with the investigations of Adhav [91].

It is observed that the expansion scalar is infinite at $t=0$ but as cosmic time increases it decreases and halts for a finite value after some time t.

For $\alpha \geq 1$ the model some times decelerate in a standard way and latter accelerate which is in accordance with present scenario.

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КОСМОЛОГИЧЕСКАЯ МОДЕЛЬ С ТЕМНОЙ ЭНЕРГИЕЙ В МОДИФИЦИРОВАННОЙ ТЕОРИИ ГРАВИТАЦИИ

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В рамках $f(R,T)$ гравитации (Harkoetal., arXiv: 1104.2669v2 [gr-qc], 2011) с разными параметрами уравнения состояния предложена модель темной энергии для нестатичного, плоского, симметричного пространства-времени, заполненного источниками идеальной жидкости. Для нахождения детерминированного решения использована специальная форма параметра торможения. Предположено, что отношение метрических потенциалов к параметру уравнения состояния пропорционально параметру асимметрии. Параметр уравнения состояния и параметр асимметрии в этой модели оказываются функциями космического времени. Обсуждены также некоторые физические и кинематические свойства предложенной модели.

Ключевые слова: *нестатичная плоская симметричная метрика:* $f(R,T)$ *- гравитация: темная энергия*

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