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BIANCHI TYPE-V MODELS IN SELF-CREATION COSMOLOGY WITH CONSTANT DECELERATION PARAMETER

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We study the Bianchi type-V cosmological model filled with perfect fluid in Barber's second self-creation theory by assuming a special law of variation for Hubble's parameter that yield a constant value of deceleration parameter. Some physical consequences of the model have been discussed in case of Zel'dovich fluid and radiation era.

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1. Introduction

Barber [1] proposed two cosmological theories. In these theories the universe is seen to be created out of self-contained gravitational, scalar and matter fields. Barber's theories allow the scalar field to interact with the particle and photon momentum four vectors, which cannot happen in the Brans-Dicke theory. Thus, Barber's first theory is modified Brans-Dicke theory. The first theory was rejected on the grounds of a gross violation of the equivalence principle, which resulted in disagreement with experiment. Later Brans [2] also showed that it was internally inconsistent. Barber's second theory is a modification of general relativity to include continuous creation and is within observational limits, thus it modifies general relativity to become a variable G-theory. In this theory, the scalar field does not directly gravitate, but simply divides the matter tensor, with the scalar acting as a reciprocal gravitational constant. The scalar field is postulated to couple to the trace of the energy-momentum tensor. The consistency of Barber's second theory motivates us to study cosmological models in this theory. Pimentel [3], Solenge [4, 5], Singh [6], Reddy [7 − 9], Reddy et al. [10, 11] and Maharaj and Beesham [12] have investigated various aspects of Barber's self creation theories. Reddy and Venkateshwarlu [13], Venkateshwarlu and Reddy [14], Shanti and Rao [15], Sanyasiraju and Rao [16], Shri and Singh [17, 18], Mohanty et al. [19], Pradhan and Vishwakarma [20, 21], Sahu and Panigrahi [22], Venkateshwarlu and Kumar [23], Singh and Kumar [24] are some of the researchers who have studied various aspects of cosmological models in self-creation theory. Singh and Kumar [24] have studied LRS Bianchi type-II models in self creation theory.

Recently, Singh et al. [25] studied Bianchi type-I models with perfect fluid in Barber's second self-creation theory of gravitation by using a special law of variation for Hubble's parameter. In this paper, we investigate Bianchi type-V cosmological solutions in Barber's second theory of gravitation in the presence of perfect fluid by assuming a special law of variation for Hubble's parameter that yields a constant value of the deceleration parameter. The law of variation of Hubble's parameter for Bianchi type-V models gives two types of solutions - power law and exponential expansion. Both the solutions are discussed for the Zel'dovich fluid [26], radiation and vacuum dominated cases. The physical behaviour of the models has also been discussed in detail for different cases.

2. Model and field equations

We consider the Bianchi type-V cosmological model in the form

$$\mathrm{d}s^2 = \mathrm{d}t^2 - A^2\mathrm{d}x^2 - B^2\mathrm{e}^{-2mx}\mathrm{d}y^2 - C^2\mathrm{e}^{-2mx}\mathrm{d}z^2\,, \tag{1}$$

where A, B and C are functions of cosmic time t only. Matter content is taken to be a perfect fluid given by the energy-momentum tensor.

$$T_{ij} = (\rho + p)v_i v_j - p g_{ij}\,, \tag{2}$$

where v_i is the four-velocity vector of the fluid satisfying

$$g_{ij}v^i v^j = 1\,, \tag{3}$$

and p and ρ are, respectively, the isotropic pressure and energy density of the fluid. We assume that the matter content obeys the equation of state

$$p = \omega\rho\,, \qquad 0 \le \omega \le 1\,. \tag{4}$$

The field equations in Barber's second self-creation theory [1] are

$$R_{ij} - \frac{1}{2}Rg_{ij} = -8\pi\phi^{-1}T_{ij} \tag{5}$$

and

$$\Box\phi = \frac{8\pi\eta}{3}T\,, \tag{6}$$

where η is a coupling constant which is to be determined from experiments. The measurements of the deflection of light restrict the value of the coupling constant to $|\eta| < 10^{-1}$.

In the limit $\eta \to 0$, the Barber's second theory approaches the standard general relativity theory in every respect. $\Box\phi = \phi^{i}_{,i}$ is the invariant D'Alembertian and T is the trace of the energy momentum-tensor that describes all non-gravitational and non-scalar field matter and energy.

The average scale factor $R(t)$ is defined by

$$R = (ABC)^{1/3}, \tag{7}$$

and average volume scale factor $V = R^3$. The Hubble's parameter H in the model is defined as

$$H = \frac{\dot{R}}{R} = \frac{1}{3}\left(\frac{\dot{A}}{A} + \frac{\dot{B}}{B} + \frac{\dot{C}}{C}\right), \tag{8}$$

where an overhead dot denotes ordinary differentiation w.r.t. t.

We also have $H = \frac{1}{3}(H_1 + H_2 + H_3)$, where $H_1 = \dot{A}/A$, $H_2 = \dot{B}/B$ and $H_3 = \dot{C}/C$, are Hubble's factors in the directions of x, y and z, respectively. The anisotropy parameter $\bar{A}$ is defined by

$$\bar{A} = \frac{1}{3}\sum_{i-1}^{3}\left(\frac{\Delta H_i}{H}\right)^2,$$

where $\Delta H_i = H_i - H$ $(i = 1, 2, 3)$.

In a comoving system of coordinates, the field Eqs. (5) and (6) for the metric (1) can be written as

$$\frac{\ddot{B}}{B} + \frac{\ddot{C}}{C} + \frac{\dot{B}\dot{C}}{BC} - \frac{m^2}{A^2} = -8\pi\phi^{-1}p\,, \tag{9}$$

$$\frac{\ddot{C}}{C} + \frac{\ddot{A}}{A} + \frac{\dot{A}\dot{C}}{AC} - \frac{m^2}{A^2} = -8\pi\phi^{-1}p\,, \tag{10}$$

$$\frac{\ddot{A}}{A} + \frac{\ddot{B}}{B} + \frac{\dot{A}\dot{B}}{AB} - \frac{m^2}{A^2} = -8\pi\phi^{-1}p\,, \tag{11}$$

$$\frac{\dot{A}\dot{B}}{AB} + \frac{\dot{B}\dot{C}}{BC} + \frac{\dot{C}\dot{A}}{CA} - \frac{3m^2}{A^2} = 8\pi\phi^{-1}\rho\,, \tag{12}$$

$$\frac{2\dot{A}}{A} - \frac{\dot{B}}{B} - \frac{\dot{C}}{C} = 0\,, \tag{13}$$

$$\ddot{\phi} + \dot{\phi}\left(\frac{\dot{A}}{A} + \frac{\dot{B}}{B} + \frac{\dot{C}}{C}\right) = \frac{8\pi\eta}{3}(\rho - 3p)\,. \tag{14}$$

Using the correspondence to general relativity, we define equivalent densities and pressure as $\rho_{\rm eq} = \rho/\phi$ and $p_{\rm eq} = p/\phi$.

If we use the equivalent energy conservation equation of general relativity on these equations, we find that

$$\dot{\left(\frac{\rho}{\phi}\right)} + \frac{\rho + p}{\phi}\left(\frac{\dot{A}}{A} + \frac{\dot{B}}{B} + \frac{\dot{C}}{C}\right) = 0\,. \tag{15}$$

3. Solution of field equations

The Einstein's field equations (9) – (14) are a coupled system of highly non-linear equations. In order to solve the field equations, we normally assume a form for the matter contents and suppose that the space-time admits killing vector symmetries. Solutions to the field equations may also be generated by applying a law of variation for Hubble's parameter which was first proposed by Berman [27] for FRW models and that yields a constant value of the deceleration parameter. The variation of Hubble's parameter assumed is consistent with observations. Berman and Gomide [28], Vishwakarma et al. [29], Singh and Kumar [24] and others have studied cosmological models with constant deceleration parameter. Recently, we have used a special law of variation for Hubbles parameter in spatially homogeneous and an isotropic Bianchi type-I space time, that also yields a constant value of the deceleration parameter [25]. According to the proposed law, the variation of the Hubble's parameter is given by

$$H = DR^{-n} = D(ABC)^{-n/3}, \tag{16}$$

where $D > 0$ and $n > 0$ are constants. From Eqs. (7) and (16), we get

$$R = (nDt + c_1)^{1/n}, \qquad n \neq 0\,, \tag{17}$$

$$R = c_2 \mathrm{e}^{Dt}, \qquad n = 0\,, \tag{18}$$

where c_1 and c_2 are constants of integration. The deceleration parameter q is defined as

$$q = \frac{-R\ddot{R}}{\dot{R}^2}\,. \tag{19}$$

From Eqs. (16) and (19), we obtain

$$q = n - 1\,. \tag{20}$$

This shows that the law (16) gives a constant value of the deceleration parameter. Equation (15) with Eq. (14) gives

$$\dot{\left(\frac{\rho}{\phi}\right)} + 3(\omega + 1)\left(\frac{\rho}{\phi}\right)\frac{\dot{R}}{R} = 0\,. \tag{21}$$

Integrating (21), we obtain

$$\frac{\rho}{\phi} = \frac{k_1}{R^{3(\omega+1)}}\,, \tag{22}$$

which together with (14) gives

$$\ddot{\phi} + 3\dot{\phi}\frac{\dot{R}}{R} = \frac{8\pi\eta}{3}(1-3\omega)\rho = \frac{8\pi\eta k_1 \phi(1-3\omega)}{3R^{3(\omega+1)}}\,, \tag{23}$$

where k_1 is a constant of integration. Integrating Eq. (13), we get

$$A^2 = k_2 BC\,, \tag{24}$$

where k_2 is a constant of integration. Without loss of generality one can take $k_2 = 1$.

From Eqs. (9) – (11), we have

$$\frac{\dot{B}}{B} - \frac{\dot{A}}{A} = \frac{k_3}{ABC}\,, \tag{25}$$

$$\frac{\dot{C}}{C} - \frac{\dot{B}}{B} = \frac{k_4}{ABC}\,, \tag{26}$$

where k_3 and k_4 are constants of integration. We solve (24) – (26) by using power law cosmology ($n \neq 0$) and exponential cosmology ($n = 0$) given by (17) and (18), respectively.

4. *Power law cosmology* $n \neq 0$

When $n \neq 0$, using Eqs. (17), (24) – (26), we obtain the line-element (1) in the form

$$\mathrm{d}s^2 = \mathrm{d}t^2 - (nDt+c_1)^{2/n}\mathrm{d}x^2 - (nDt+c_1)^{2/n}\exp\left[\frac{2k_3}{D(n-3)}(nDt+c_1)^{(n-3)/n}\right]\mathrm{e}^{-2mx}\mathrm{d}y^2$$

$$-(nDt+c_1)^{2/n}\exp\left[\frac{-2k_3}{D(n-3)}(nDt+c_1)^{(n-3)/n}\right]\mathrm{e}^{-2mx}\mathrm{d}z^2\,, \tag{27}$$

where $n \neq 3$. In this case, Eq. (23) reduces to

$$\ddot{\phi} + 3\dot{\phi}D(nDt+c_1)^{-1} = \frac{8\pi\eta k_1(1-3\omega)\phi}{3(nDt+c_1)^{3(\omega+1)/n}}\,. \tag{28}$$

Now, we discuss the model with Zel'dovich fluid, radiation dominated case and the vacuum case.

4.1. Zel'dovich fluid distribution

It corresponds to the equation of state $\rho = p$. In this case, Eq. (28) on integration gives

$$\phi(t) = \cos\left[\frac{\sqrt{48\pi\eta c_3}}{3D(n-3)}(nDt + c_1)^{(n-3)/n} + c_4\right], \tag{29}$$

where c_3 and c_4 are constants of integration. The energy density ρ and pressure p of the fluid are given by

$$\rho = p = k_1(nDt + c_1)^{-6/n}\cos\left[\frac{\sqrt{48\pi\eta c_3}}{3D(n-3)}(nDt + c_1)^{(n-3)/n} + c_4\right]. \tag{30}$$

For the reality condition $\rho > 0$ to hold, it is necessary that $k_1 > 0$.

Now, the expressions for some other cosmological parameters, the model spatial volume V, expansion scalar θ, shear and other, are given by

$$V = (nDt + c_1)^{n/3}\mathrm{e}^{-2mx}, \tag{31}$$

$$\theta = \frac{3D}{(nDt + c_1)}, \tag{32}$$

$$\sigma^2 = \frac{k_3}{(nDt + c_1)^{6/n}}, \tag{33}$$

$$H_1 = \frac{D}{(nDt + c_1)}, \tag{34}$$

$$H_2 = \frac{k_3}{(nDt + c_1)^{3/n}} + \frac{D}{(nDt + c_1)}, \tag{35}$$

$$H_3 = \frac{D}{(nDt + c_1)} - \frac{k_3}{(nDt + c_1)^{3/n}}, \tag{36}$$

$$\bar{A} = \frac{2}{3}\frac{k_3^2}{D^2(nDt + c_1)^{(6-2n)/n}}. \tag{37}$$

In the model, we observe that at $t = -c_1/(nD) = t_0$, the spatial volume V is zero and the expansion scalar θ is infinite which shows that at $t = t_0$, the universe starts evolving with zero volume and infinite rate of expansion. For $n > 0$, at $t = t_0$, the energy density ρ and pressure p are infinite, the anisotropy parameter $\bar{A}$ and shear scalar σ are also infinite at the initial epoch $t = t_0$. As t increases, the spatial volume increases and the expansion scalar decreases. Thus, the expansion rate decreases as time increases. As $t \to \infty$, the spatial volume V becomes infinitely large. The parameters ρ, p, σ, H_1, H_2 and H_3 tend to zero when $t \to \infty$ for $n > 0$. Therefore, the model essentially gives an empty universe for large t. The ratio $\sigma/\theta \to 0$ at $t \to \infty$, which shows that model approaches isotropy for large values of t. Clearly the scalar field remains finite throughout the evolution of universe. In the limit $\eta \to 0$, the solutions approach Einstein theory in all respects. The model represents shearing, non-rotating and expanding universe with a big-bang start.

4.2. Radiation dominated solution

From Eq. (28)

$$\phi = c_5 \frac{(nDt + c_1)^{(n-3)/n}}{D(n-3)} + c_6 \,, \tag{38}$$

using (38) in (22), we get

$$\rho = 3p = k_1 (nDt + c_1)^{-4/n} \left[c_5 \frac{(nDt + c_1)^{(n-3)/n}}{D(n-3)} + c_6 \right], \tag{39}$$

where c_5 and c_6 are integration constants. Other cosmological parameters are:

$$V = (nDt + c_1)^{n/3} \mathrm{e}^{-2mx}, \tag{40}$$

$$\theta = \frac{3D}{(nDt + c_1)} \,, \tag{41}$$

$$\sigma^2 = \frac{k_3}{(nDt + c_1)^{6/n}} \,, \tag{42}$$

$$H_1 = \frac{D}{(nDt + c_1)} \,, \tag{43}$$

$$H_2 = \frac{k_3}{(nDt + c_1)^{3/n}} + \frac{D}{(nDt + c_1)} \,, \tag{44}$$

$$H_3 = \frac{D}{(nDt + c_1)} - \frac{k_3}{(nDt + c_1)^{3/n}} \,, \tag{45}$$

$$\bar{A} = \frac{2}{3} \frac{k_3^2}{D^2 (nDt + c_1)^{(6-2n)/n}} \,. \tag{46}$$

In this case, the universe starts with an infinite rate of expansion from $t = t_0$ where $t_0 = -c_1/(nD)$. The energy density, scalar field and pressure are infinite at the initial singularity at t_0 provided $n < 3$. The space time exhibits 'point type' singularity at $t = t_0$. As t increases, spatial volume V increases, but the rate of expansion slows down. All physical parameters decrease with time. Spatial volume V becomes infinitely large as $t \to \infty$. The energy density, pressure, anisotropic parameter and directional Hubble's factors tend to zero as $t \to \infty$. The anisotropic parameter vanishes as $t \to \infty$. The shear σ is infinite at $t = t_0$ and tends to zero as $t \to \infty$. Since $\sigma/\theta \to 0$, the model approaches isotropy for large values of t. Therefore, the model represents a non-rotating, shearing and expanding universe with a big-bang start.

4.3. *Vacuum solution* ($\rho = p = 0$)

In this case, scalar field ϕ and cosmological parameters V, θ and σ^2 are:

$$\phi = c_5 \frac{(nDt + c_1)^{(n-3)/n}}{D(n-3)} + c_6 \,. \tag{47}$$

$$\theta = \frac{3D}{(nDt + c_1)} \,, \tag{48}$$

$$\sigma^2 = \frac{k_3}{(nDt + c_1)^{6/n}} \,, \tag{49}$$

$$\bar{A} = \frac{2}{3} \frac{k_3^2}{D^2 (nDt + c_1)^{(6-2n)/n}} \,. \tag{50}$$

Clearly, the spatial volume is zero and expansion scalar is infinite at the initial singularity $t = t_0$, where $t_0 = -c_1/(nD)$. The universe starts expanding with zero volume and infinite rate of expansion. At $t = t_0$, the space time exhibits 'point type' singularity. Scalar field, anisotropy parameter and shear scalar also tend to infinity at initial singularity provided $n < 3$. As t increases, spatial volume increases but the rate of expansion slows down. The scalar field and the isotropic parameter decrease as time increases provided $n < 3$. The expansion scalar θ, shear σ and anisotropy parameter $\bar{A}$ vanish asymptotically. The ratio σ/θ tends to zero when $t \to \infty$, thus, the model approaches isotropy.

5. *Exponential cosmology* ($n = 0$)

From (18), (24) – (26), we obtain the line-element (1) in the form

$$\mathrm{d}s^2 = \mathrm{d}t^2 - c_2^2 \exp(3Dt)\mathrm{d}x^2 - \exp\left(2Dt - \frac{2k_3 \mathrm{e}^{-3/Dt}}{3Dc_2^3}\right) \mathrm{e}^{-2mx} \mathrm{d}y^2$$

$$-c_2^4 \exp\left(2Dt + \frac{2k_3 \mathrm{e}^{-3/Dt}}{3Dc_2^3}\right) \mathrm{d}z^2 \,, \tag{51}$$

In this case from (23), we obtain

$$\ddot{\phi} + 3\dot{\phi} D c_2 = \frac{8\pi\eta k_3 (1 - 3\omega)\phi}{3(c_2 \mathrm{e}^{Dt})^{3(\omega+1)}} \,. \tag{52}$$

We analyze the model for stiff matter, radiation dominated case and the vacuum case in the following subsections.

5.1. *Stiff fluid model*

Stiff fluid corresponds to the equation of state $\rho = p$. In this case, Eq. (52) yields an exact solution for the scalar field as

$$\phi(t) = \cos\left[\frac{\sqrt{16\pi\eta c_7}}{-3c_2^3 D}\mathrm{e}^{-3Dt} + c_8\right], \tag{53}$$

where c_7 and c_8 are constants of integration. The energy density ρ and pressure p are given by

$$\rho = p = k_1 \mathrm{e}^{-6Dt}\cos\left[\frac{\sqrt{16\pi\eta c_7}}{-3c_2^3 D}\mathrm{e}^{-3Dt} + c_8\right], \tag{54}$$

$$V = c_2^3 \mathrm{e}^{3Dt}\mathrm{e}^{-2mx}, \qquad \theta = 3D\,, \tag{55}$$

$$\sigma^2 = \frac{k_3}{3c_2^3}\mathrm{e}^{-6Dt}, \tag{56}$$

$$H_1 = D\,, \tag{57}$$

$$H_2 = \frac{k_3}{c_2^3}\mathrm{e}^{-3Dt} + D\,, \tag{58}$$

$$H_3 = D - \frac{k_3}{c_2^3}\mathrm{e}^{-3Dt}\,, \tag{59}$$

$$\bar{A} = \frac{2}{3}\frac{k_3^2}{D^2 c_2^6}\mathrm{e}^{-6Dt}\,. \tag{60}$$

The model has no initial singularity. Energy density, pressure, spatial volume, scale factors, scalar field and all other cosmological parameters are constant at $t = 0$. The universe starts evolving with a constant volume and expands with exponential rate. The energy density and pressure decrease while spatial volume increases as the cosmic time increases. As $t \to \infty$, energy density and pressure tend to be zero. The Hubble's factors tend to constant values and the anisotropy parameter tends to zero as $t \to \infty$. The scalar field ϕ remains finite during the whole span of evolution. It is interesting to note that the expansion scalar is constant for $0 < t < \infty$ and, therefore, the model represents uniform expansion. The shear scalar σ is constant initially and tends to become zero asymptotically. Since $\sigma/\theta \to 0$ as $t \to \infty$, the model approaches isotropy for large values of t. The universe will become infinitely large for large values of t. Also $\lim_{t\to 0} \rho/\theta = constant$. Thus, the model approaches homogeneity and matter is dynamically negligible near the origin. This is similar to the result already given by Collins [30]. The model represents shearing, non-rotating and expanding universe with a finite start.

5.2. Radiation dominated solution ($\rho = 3p$)

In this case, the scalar field ϕ, energy density ρ and pressure p are given by

$$\phi(t) = \frac{-c_9}{3c_2^3 D} e^{-3Dt} + c_{10}\,, \tag{61}$$

$$\rho = 3p = k_1 e^{-4Dt}\left[\frac{-c_9}{3c_2^3 D} e^{-3Dt} + c_{10}\right], \tag{62}$$

where c_9, c_{10} are constants of integration. Other cosmological parameters are:

$$\theta = 3D\,, \qquad \sigma^2 = \frac{k_3}{3c_2^3} e^{-6Dt},$$

$$H_1 = D\,, \tag{63}$$

$$H_2 = \frac{k_3}{c_2^3} e^{-3Dt} + D\,, \tag{64}$$

$$H_3 = D - \frac{k_3}{c_2^3} e^{-3Dt}\,, \tag{65}$$

$$\bar{A} = \frac{2}{3}\frac{k_3}{D^2 c_2^6} e^{-6Dt}\,. \tag{66}$$

We must have $k_1 > 0$ for the energy density to be positive. The model has no initial singularity. Initially, spatial volume, energy density, pressure and other cosmological parameters are constant. The universe starts evolving with a constant volume and expands with exponential rate. When t increases, the scalar field, energy density and pressure decrease. As $t \to \infty$, density and pressure tend to zero. The scalar field and Hubble's factors tend to constant values and anisotropy parameter tends to zero as $t \to \infty$. The scalar field remains finite during the whole span of evolution. The model expands uniformly and approaches isotropy for large value of t.

5.3. Vacuum solution ($\rho = p = 0$)

In this case, the behavior of the model is the same as in section 5.2.

6. Conclusion

In this paper we obtained exact solutions of the field equations for the orthogonal Bianchi type-V space-time in Barber's second self creation theory of gravitation. Cosmological models with constant deceleration parameter have been presented for $n \neq 0$ and $n = 0$ cosmologies. There are two solutions: one is the power-law solution and other is exponential solution. We discuss both the solutions for stiff fluid, radiation and vacuum cases. We discuss geometrical and kinematical properties of different parameters in detail for each phase. The nature of singularities of the models has been clarified and explicit forms of scale factors have been obtained in each case. For $n \neq 3$, the spatial volume V grows linearly with cosmic time. It has been observed that the model represents shearing, non-rotating and expanding universe with a big-bang start. If the deceleration parameter q is positive, the model decelerates and for q to be negative, the model inflates. For $n = 0$, $q = -1$. Incidentally this value of q leads to $\mathrm{d}H/\mathrm{d}t = 0$, which implies the greatest value of Hubble's parameter and the fastest rate of expansion of universe. This type of solution is consistent with recent observations of supernovae Ia (Reiss et al. [31]; Perlmutter et al. [32]) that require the present universe to be accelerating. The model has singular origin for $n \neq 0$ and non-singular origin for $n = 0$. For $n = 0$, the model represents a shearing, non-rotating and expanding universe with a finite start. The universe becomes isotropic for large values of t. It is found that if $\eta \to 0$, the Barber's self creation theory tends to general theory of relativity in all respects.

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BIANCHIJEVI MODELI TIPA V U SAMOTVORNOJ KOZMOLOGIJI SA STALNIM PARAMETROM USPORAVANJA

Proučavamo Bianchijev kozmološki model svemira tipa V ispunjenog perfektnom tekućinom u Barberovoj samotvornoj teoriji, pretpostavljajući poseban zakon o ovisnosti Hubbleovog parametra što daje stalnu vrijednost parametra usporavanja. Raspravljamo neke ishode modela za Zel'dovichevu tekućinu i za doba zračenja.