Assuming that supernovae type Ia (SNe Ia) are standard candles one could use them to test cosmological theories. The Hubble Space Telescope team analyzed 186 SNe Ia to test the Standard Cosmological model (SC) associated with expanded lengths in the Universe and evaluate its parameters. We use the same sample to determine parameters of Conformal Cosmological model (CC) with relative reference units of intervals, so that conformal quantities of General Relativity are interpreted as observables. We concluded, that really the test is extremely useful and allows to evaluate parameters of the model. From a formal statistical point of view the best fit of the CC model is almost the same quality approximation as the best fit of SC model with $\Omega_\Lambda = 0.72, \Omega_m = 0.28$. As it was noted earlier, for CC models, a rigid matter component could substitute the $\Lambda$-term (or quintessence) existing in the SC model. We note that a free massless scalar field can generate such a rigid matter. We describe results of our analysis for more recent "gold" data (for 192 SNe Ia).

**Keywords**: General Relativity and Gravitation; Cosmology; Observational Cosmology; Cosmological tests; Supernovae

1. Introduction

Now there is enormous progress in observational and theoretical cosmology and even it is typically accepted that cosmology enters into an era of precise science (it means that a typical accuracy of standard parameter determination is about few percents), despite, there are different approaches including alternative theories of gravity to fit observational data (see recent reviews for references). Some classes of theories
could be constrained by Solar system data even if they passed cosmological tests. Thus, all the theories should pass all possible tests including cosmological ones.

Since the end of the last century distant supernovae data is a widespread test for all theoretical cosmological models in spite of the fact the correctness of the hypothesis about SNe Ia as the perfect standard candles is still not proven. However, the first observational conclusion about accelerating Universe and existence of non-vanishing Λ-term was done with the cosmological SNe Ia data. Therefore, typically standard (and alternative) cosmological approaches are checked with the test.

Conformal cosmological models, where all observables are identified with the scale-invariant quantities of GR introduced yet by Lichnerowicz, are also discussed among other possibilities. The Conformal Cosmology is based on the Dirac version of the GR. Dirac modified the accepted General Relativity (GR) in spirit of the simplified Weyl’s geometry, which means that “a new action principle was set up, much simpler than Weyl’s, but requiring a scalar field function” (called here as dilaton) “to describe the gravitation field, in additional to . The Dirac version of GR

\[
S_{\text{Dirac}} = -\phi^2 \int d^4x \left[ e^{-2D} \sqrt{-g} R^{(4)}(\tilde{g}) + e^{-D} \partial_{\mu} \left( \sqrt{-g} g^{\mu\nu} \partial_{\nu} e^{-D} \right) \right]
\]

is compatible with the choice of the Lichnerowicz variables $|\tilde{g}^{(3)}| = 18$ as measurable ones that scale all masses. The action is scale-invariant in contrast to the Brans – Dicke theory.

The Conformal Cosmology is based on the Weyl definition of the measurable interval as the ratio of the Einstein interval and units defined as reversed masses

\[
1 + z = \frac{\lambda_0}{\lambda_0 a(t)} \frac{m_0}{\lambda_0 m_0} = \frac{\lambda_0}{\lambda_0 [a(t)m_0]},
\]

where $\lambda_0$ is the wave length of a photon emitted at the present-day instant and $m_0$ is the standard mass defining the units of measurements. This Weyl definition of the measurable interval gives a possibility to consider two alternatives: the Standard Cosmology (SC)

\[
(1 + z)_{\text{SC}} = \frac{\lambda_0}{[\lambda_0 a(t)]}
\]

if $a$ is jointed to a length $\lambda_0$ (that means expanded lengths in a universe), or the Conformal Cosmology (CC)

\[
(1 + z)_{\text{CC}} = \frac{m_0}{[a(t)m_0]}
\]

if we joint $a$ to a mass $m_0$ (that means running masses). The construction of all observable CC-quantities is based on the conformal postulate in accord to which all observable CC-quantities $F^{(n)}_{\text{cc}}$ with conformal weight $(n)$ are equal to the SC ones.
$F_s^{(n)}$ multiplied by the cosmological scale factor to the power $(-n)$

$$F_c^{(n)} = a^{-n} F_s^{(n)}$$

(5)

In accord with the conformal postulate (5) the CC-time is greater than the SC one, and all CC-distances, including the CC-luminosity distance $\ell_c$, are longer than the SC-ones $\ell_s = a\ell_c$, because all intervals are measured by clocks of mass $\text{const}/a$.

Conformal symmetry means that the really measurable quantity is the ratio $[M_e L_e]/[M_0 L_0] = a_e$ where $[M_e L_e]$ is the conformal-invariant product of mass of the atom $M_e$ (reflecting its size), and the wave-length $L_e$ of the atom photon, at the time of emission $e$, and $[M_0 L_0]$ is the similar product value at present day.

In the papers devoted to the applications of the conformal symmetry in order to study and calculate the short-distance effects in quantum gravity one counted that the source of the cosmological scale factor ($a_e$) growth is the expansion of the lengths (i.e. $L_e = a_e L_0, M_e = M_0$). In contrast to these papers, in our approach we select another possible alternative: (i.e. $M_e = a_e M_0, L_e = L_0$).

First attempts to analyze SNe Ia data to evaluate parameters of CC models were done, so it was used only 42 high redshift type Ia SNe but after that it was analyzed a slightly extended sample. In spite of a small size of the samples used in previous attempts to fit CC model parameters, it was concluded that if $\Omega_{\text{rig}}$ is significant in respect to the critical density, CC models could fit SNe Ia observational data with a reasonable accuracy. After that a possibility to fit observational SNe Ia data with CC models was seriously discussed by different authors among other alternatives.

An aim of the paper is to check and clarify previous conclusions about possible bands for CC parameters with a more extended (and more accurate) sample used commonly to check standard and alternative cosmological models. The HST cosmological SNe Ia team have corrected data of previous smaller samples as well and also considered possible non-cosmological but astronomical ways to fit observational ways and concluded that some of them such a replenishing dust (with $\Omega_m = 1, \Omega_\Lambda = 0.$) could fit observational data pretty well even in respect to the best fit cosmological model.

The content of the paper is the following. In Section 2, the basic CC relations are reminded. In Section 3, a magnitude-redshift relation for distant SNe is discussed. In Section 4, results of fitting procedure for CC models with the ”gold” and ”silver” sample are given. Conclusions are presented in Section 5.

2. Conformal Cosmology Relations

We will remind basic relations for CC model parameters (see papers for details) considering the General Relativity with an additional scalar field $Q$, as usually people did to introduce quinessence (earlier, the approach was used for inflationary
cosmology, see for example, paper [16] and references therein)

\[ S = S_{\text{Dirac}} + \int d^4x \sqrt{-g} \left[ \frac{1}{2} \partial_{\mu} Q \partial^{\mu} Q - V(Q) \right]; \]  

(6)

here we used the natural units

\[ M_{\text{Planck}} \sqrt{\frac{3}{8\pi}} = \hbar = c = 1, \]  

(7)

therefore, we have the following expressions for density and pressure of the scalar field \( p_Q \) and \( \rho_Q \), respectively

\[
p_Q(t) = \frac{1}{2} \dot{Q}^2 + V(Q), \\
\rho_Q(t) = \frac{1}{2} \dot{Q}^2 - V(Q),
\]  

(8)

and equation of state (EOS) such as \( p_Q = w_Q \rho_Q \), where

\[
w_Q = \frac{\frac{1}{2} \dot{Q}^2 - V(Q)}{\frac{1}{2} \dot{Q}^2 + V(Q)},
\]  

(9)

\((-1 \leq w_Q \leq 1\), for "natural" potentials \( V(Q) \geq 0\)). In contrast with quintessence model where one uses typically \( \dot{Q}^2 \ll V(Q) \), below for CC model we will use an approximation \( \dot{Q}^2 \gg V(Q) \) (for a standard representation of the potential \( V(Q) = \frac{1}{2} m Q^2 \), where \( m \) is a mass of the field, the approximation corresponds to a massless field model) and we have

\[
w_Q = \frac{\frac{1}{2} \dot{Q}^2}{\frac{1}{2} \dot{Q}^2} = 1,
\]  

(10)

or on the other words, a rigid EOS for the scalar field \( p_Q = \rho_Q \) \( (p_{\text{rig}} = \rho_{\text{rig}} \), since for our future needs an origin of the EOS is not important, hereafter, we will call the component such as the rigid matter).

The conformal postulate means that CC-intervals

\[
ds_c^2 = \frac{ds^2}{a^2} = (d\eta)^2 - (dx^k)^2,
\]  

(11)

are greater than SC-intervals, CC-time \( t_c = \eta = \int dt_s/a \) is greater than SC-time \( t_s = t \) CC-luminosity-distance

\[
\ell_c = \frac{\ell_s}{a},
\]  

(12)

is longer than the SC-one, conformal masses scaled by the factor \( a \)

\[
m_c = m_0 a(\eta)
\]  

(13)

are less than constant SC masses \( m_s = m_0 \), and a constant conformal temperature \( T_c = a T_s = T_0/a \) is less that the SC-temperature \( T_s = T_0/a \).
In homogeneous approximation both SC and CC are described by

\[(a')^2 = \rho_c(a)\]  \hspace{1cm} (14)

where \(a'\) is the derivative of the cosmological scale factor \(a\) with respect to conformal time,

\[\rho_c(a) = \rho_0 \sum_{J=-2,0,1,4} \Omega_J a^J\]  \hspace{1cm} (15)

is the conformal energy density connected with the SC one by the transformation

\[\rho_c(a) = a^4 \rho_s(a),\]  \hspace{1cm} (16)

and \(\Omega_J\) is partial energy density marked by index \(J\) running a set of values \(J = -2\) (rigid), \(J = 0\) (radiation), \(J = 1\) (mass), and \(J = 4\) (\(\Lambda\)-term) in correspondence with a type of matter field contributions; here \(\sum_{J=-2,0,1,4} \Omega_J = 1\) is assumed. The case \(J = -2\) corresponds to a rigid state, where the energy density coincides with the pressure one \(\rho = p\). The rigid state can be formed by the massless scalar field \(Q\) with the integral of motion

\[a^2 Q' = \sqrt{\rho_0}.\]

In terms of the standard cosmological definitions of the redshift

\[1 + z \equiv \frac{1}{a(\eta)},\]  \hspace{1cm} (17)

the density parameter \(\Omega_c(z) = \sum_{J=-2,0,1,4} \Omega_J a^J\) in Eq. (15) takes the form

\[\Omega_c(z) = \Omega_{\text{rig}}(1 + z)^2 + \Omega_{\text{rad}} + \Omega_m + \frac{\Omega_{\Lambda}}{(1 + z)^4}.\]  \hspace{1cm} (18)

Then the equation (14) takes the form

\[H_0 \frac{d\eta}{dz} = \frac{1}{(1 + z)^2} \frac{1}{\sqrt{\Omega_c(z)}},\]  \hspace{1cm} (19)

and determines the dependence of the conformal time on the redshift factor. Recall this conformal time - redshift relation is valid in both the SC and CC, where this conformal time is used for description of a light ray

A light ray traces a null geodesic, i.e. a path for which the conformal interval \((ds^2) = 0\) thus satisfying the equation \(dr/d\eta = 1\). As a result we obtain for the coordinate distance \(r\) as a function of the redshift

\[H_0 r(z) = \int^z \frac{dz'}{(1 + z')^2} \frac{1}{\sqrt{\Omega_c(z')}}.\]  \hspace{1cm} (20)

This coordinate distance – redshift relation (20) is a basis of the luminosity distance – redshift relation in SC. The derivation of luminosity-distance – redshift relation in CC is based on the calculation of this relation in SC and the conformal postulate and (12).
In order to calculate the SC luminosity-distance – redshift relation consider a distant source of photons. In conformal coordinates, photons behave exactly as in Minkowski space. Hence, conformal times between emissions of two subsequent photons and absorptions of these photons are equal. (This is true both in SC and CC.) The number of photons emitted per unit conformal time and absorbed in unit conformal time by a detector covering entire sphere around the source is the same irrespectively of the position of this sphere,

\[ \frac{dn}{d\eta_{\text{abs}}} = \frac{dn}{d\eta_{\text{emis}}} \]  

(21)

Physical times in both cosmologies between the emission emissions and absorptions are different, in SC because \( dt = a d\eta \), and in CC because time is measured by clocks of mass const/\( a \). Hence

\[ \frac{dn}{d\eta_{\text{abs}}} = a(z) \frac{a(0)}{a_0} \frac{dn}{d\eta_{\text{emis}}} \]  

(22)

where \( a(z) \) is the scale factor at emission, and \( a_0 = 1 \) is the scale factor at absorption. This formula is valid both in SC and in CC.

The second effect is redshift. Overall, the energy flow through entire sphere is

\[ \frac{d\varepsilon}{dt} = \frac{1}{1 + z} \frac{1}{1 + z} L \]  

(23)

where the first factor is due to redshift, the second factor is due to the effect (22), and \( L \) is absolute luminosity of the source. This formula is valid both in SC and in CC.

Finally, to obtain visible SC luminosity, one has to divide (23) by the present area of the sphere. This gives for the visible SC luminosity is equal to energy of per unit time and per unit surface,

\[ \frac{d\varepsilon}{ds dt} = \frac{1}{1 + z} \frac{1}{1 + z} \frac{L}{4\pi r(z)^2} \]  

(24)

Defining, as usual, the SC luminosity-distance \( \ell_s \) such that

\[ \frac{d\varepsilon}{ds dt} = \frac{1}{4\pi \ell_s^2} L \]  

(25)

one finds the SC luminosity-distance – redshift relation

\[ \ell_s(z) = (1 + z)^2 r_s = (1 + z)r(z) , \]  

(26)

The CC luminosity-distance – redshift relation can be obtained from (12) in accord with the cosmological postulate (5)

\[ \ell_c(z) = (1 + z)^2 \ell_s(z) = (1 + z)^2 r(z) . \]  

(27)

because all measurable lengths in CC and SC differ, and all observable lengths (11) in CC (4) contain an additional factor (1 + z).
Table 1. The fits for CC models for the total sample with different constraints on $\Omega_m$ (the best fits are shown in first, second and third rows, two almost best fits are presented in fourth and fifth rows).

| Constraints on $\Omega_m$ | $\Omega_m$ | $\Omega_\Lambda$ | $\Omega_{rad}$ | $\Omega_{rig}$ | $\chi^2$ |
|--------------------------|-----------|------------------|---------------|--------------|---------|
| No constraints           | -4.13     | 3.05             | 0.05          | 2.085        | 226.64  |
| $\Omega_m \geq 0.$      | 0.        | 0.18             | 0.            | 0.80         | 242.76  |
| $0.2 \leq \Omega_m \leq 0.3$ | 0.2      | 0.013            | 0.            | 0.75         | 244.67  |
| $0.2 \leq \Omega_m \leq 0.3$ | 0.29     | 0.0              | 0.            | 0.7          | 246.58  |
| $0.2 \leq \Omega_m \leq 0.3$ | 0.27     | 0.0              | 0.            | 0.72         | 245.66  |

3. Magnitude-Redshift Relation

Typically to test cosmological theories one should check a relation between an apparent magnitude and a redshift. In both SC and CC models it should be valid the effective magnitude-redshift relation:

$$\mu(z) \equiv m(z) - M = 5 \log[H_0\ell(z)] + \mathcal{M},$$

(28)

where $m(z)$ is an observed magnitude, $M$ is the absolute magnitude, $\mathcal{M}$ is a constant with recent experimental data for distant SNe. Values of $\mu_i$, $z_i$ and $\sigma_i$ could be taken from observations of a detected supernova with index $i$ ($\sigma_i^2$ is a dispersion for the $\mu_i$ evaluation). Since we deal with observational data we should choose model parameters to satisfy an array of relations \cite{28} by the best way because usually, a number of relations is much more than a number of model parameters and there are errors in both theory and observations (as usual we introduce indices for the relations corresponding to all objects). Typically, $\chi^2$-criterium is used to solve the problem, namely, we calculate

$$\chi^2 = \sum_i \frac{(\mu_i^{\text{theor}} - \mu_i)^2}{\sigma_i^2},$$

(29)

where $\mu_i^{\text{theor}}$ are calculated for given $z_i$ with the assumed theoretical model and after that we can evaluate the best fit model parameters minimizing $\chi^2$-function.

4. Total sample analysis

For the standard cosmological model for the 186 SNe (the "gold" and "silver" sample)\cite{4} a minimum of the $\chi^2$-function gives us $\Omega_m = 0.28$ ($\chi^2_{\text{SC flat}} = 232.4$) and $\Omega_m = 0.31, \Omega_\Lambda = 0.80$ assuming $|\Omega_k| \leq 0.11$ ($\chi^2_{\text{SC flat}} = 231.0$). Since other cosmological tests dictate that the Universe should be almost flat and $\Omega_m = 0.28$ is an acceptable value\cite{2} we choose the flat SC model for a reference.

In Fig. 1 we compare the SC and CC fits for the effective magnitude-redshift relation if we will not put any constraint on $\Omega_m$ (in this case we assume that SNe Ia data is the only cosmological test for CC models we obtain the best fit expressed\cite{5}.

\footnote{To express differences in quality of spectroscopic and photometric data the supernovae were separated into "high-confidence" ("gold") and "likely but not certain" ("silver") subsets.}
Fig. 1. $\mu(z)$-dependence for cosmological models in SC and CC. The data points include 186 SN Ia (the "gold" and "silver" sample) used by the cosmological supernova HST team. For a reference we use the best fit for the flat standard cosmology model with $\Omega_m = 0.27, \Omega_\Lambda = 0.73$ (the thick dashed line), the best fit for CC is shown with the thick solid line. For this CC model we do not put any constraints on $\Omega_m$.

Table 2. The $\chi^2$ values for pure flat CC models for the total sample. The models are shown in Figs. 1, 2 as references.

| Model types | $\Omega_m = 1$ | $\Omega_\Lambda = 1$ | $\Omega_{\text{rad}} = 1$ | $\Omega_{\text{rig}} = 1$ |
|-------------|---------------|-----------------|----------------|----------------|
| $\chi^2$    | 924.27        | 4087.93         | 478.42         | 276.71         |

in the first row in Table 1. Analyzing the curves corresponding to the best fits for SC and CC models one can say that they almost non-distinguishable, moreover the best fit CC provide even better the $\chi^2$ value (see first row in Table 1). We would not claim that we discovered a cosmological model with negative $\Omega_m$, but we would like to note that the best CC and SC fits are almost non-distinguishable from a formal statistical point of view (the thick solid and long dashed lines, respectively in Fig. 1). An appearance of the fit with negative $\Omega_m$ can be caused also by systematical errors in observational data. Sometimes new physical phenomena are introduced qualitatively with the same statistical arguments (such as an introduction of the phantom energy, for instance), but if we should follow a more conservative approach, we could conclude that in this case we should simply put extra constraints on $\Omega_m$ to have no contradictions to other cosmological (and astronomical) tests. So, if we put "natural" constraints on $\Omega_m \geq 0$, the best fit parameters for CC model are presented in second row in Table 1. In this case the $\chi^2$ difference between two CC models ($\Delta \chi^2 \approx 16$) is not very high and a difference between this fit and the SC best
Fig. 2. $\mu(z)$-dependence cosmological models in SC and CC. As in previous figure, the data points include 186 SN Ia (the "gold" and "silver" sample) used by the cosmological supernova HST team and for a reference we use the best fit for the flat standard cosmology model with $\Omega_m = 0.27, \Omega_\Lambda = 0.73$ (the thick dashed line), the best fit for CC is shown with the thick solid line. For this CC model we assume $\Omega_m \in [0.2, 0.3]$. The fit for a flat model is about $\Delta \chi^2 \approx 10$ (or less than 5%), it means the CC fit is at an acceptable level. For references, we plotted also pure flat CC models, so that rigid, matter, lambda and radiation models are shown with thin dotted, short dashed, dot dash, dash dot dot dot lines, respectively. Corresponding $\chi^2$ values are given in Table 2. One can see that only pure flat rigid CC model has relatively low $\chi^2$ values (and it could be accepted as a rough and relatively good fit for cosmological SNe Ia data), but other models should be definitely ruled out by the observational data.

So, if we put further constraints on $0.2 \leq \Omega_m \leq 0.3$ based on measurements of clusters of galaxies and other cosmological arguments,[20] the best fit parameters for CC model are presented in third row in Table 1. In this case the $\chi^2$ difference between two CC models ($\Delta \chi^2 \approx 18$) is not very high also and a difference between $\chi^2$ for the CC and SC models is about $\Delta \chi^2 \approx 12$ (or about 5%), it means the CC fit is at an acceptable level. Dependence of $\chi^2$ on $\Omega_m$ is very weak and we present intermediate fits for CC model in fourth and fifth rows in Table 1 (there is a valley of $\chi^2$ function in the $\Omega_m$ direction). The best fit for a CC model with parameters given in third row in Table 1 is shown as the optimal fit for the CC model in Fig. 2 with the solid thick line. Other lines are the same as in Fig. 1 and they are shown for references.
In the section we describe results of our analysis for more recent "gold" data (for 192 SNe Ia) (21) where the authors collected observational data published earlier (22,23). These SNe Ia are shown in Fig. 3. For the standard flat cosmological model $\chi^2 = 196.1$, meanwhile for the best fit for CC model $\chi^2 = 203.03$, so the difference for these two approximations is only few percent, therefore.

5. Analysis for more recent "gold" SNe Ia data

In the section we describe results of our analysis for more recent "gold" data (for 192 SNe Ia) (21) where the authors collected observational data published earlier (22,23). These SNe Ia are shown in Fig. 3. For the standard flat cosmological model $\chi^2 = 196.1$, meanwhile for the best fit for CC model $\chi^2 = 203.03$, so the difference for these two approximations is only few percent, therefore.

6. Conclusions

Using "gold" and "silver" 186 SNe Ia (18) we confirm in general and clarify previous conclusions about CC model parameters, done earlier with analysis of smaller sample of SNe Ia data (36) that the pure flat rigid CC model could fit the data relatively well since $\Delta \chi^2 \approx 44.3$ (or less than 20 %) in respect of the standard cosmology flat
model with $\Omega_m = 0.28$. Other pure flat CC models should be ruled out since their $\chi^2$ values are too high.

For the total sample, if we consider CC models with a "realistic" constraint $0.2 \leq \Omega_m \leq 0.3$ based on other astronomical or cosmological arguments except SNe Ia data, we conclude that the standard cosmology flat model with $\Omega_m = 0.28$ is still preferable in respect to the fits for the CC models (with $\Omega_m = 0.2$ and $\Omega_{\text{rig}} = 0.75$ or $\Omega_m = 0.27$ and $\Omega_{\text{rig}} = 0.72$, for instance, see third and fifth rows in Table 1), but the preference is not very high (about 5% in relative units of $\chi^2$ value), so the CC models could be adopted as acceptable ones taking into account possible sources of errors in the sample and systematics.

Thus, for CC model fits calculated with SNe Ia data, in some sense, a rigid equation of state could substitute the $\Lambda$-term (or quintessence) in the Universe content. As it was mentioned above the rigid matter can be formed by a free massless scalar field.

The best CC models provide almost the same quality fits of SNe Ia data as the best fit for the SC flat model, however the last (generally accepted) model is more preferable.

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