Dependence of standardization parameters of type Ia supernova light curves on redshift

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Abstract

The paper shows that the parameters X_1 and C used to standardize the luminosity of type Ia supernovae in the SALT2 model are highly dependent on redshift. This leads to the fact that during standardization, with increasing z, the average absolute stellar magnitude of type Ia supernovae artificially increases and, therefore, for a given apparent magnitude, we attribute to them, on average, a greater distance than they actually have. And therefore it is believed that they are receding with acceleration. Therefore, such standardization is unsuitable for measuring distances to type Ia supernovae. If the standardization parameter $(-\alpha X_1 + \beta C)$ is replaced by the redshift-dependent parameter (ϵz), then the parameter Ω_Λ turns into 0 in the ΛCDM model.

Keywords: *Supernovae Ia; Luminosity standardization; Cosmological Parameters; Cosmology*

1. Introduction

Type 1a supernovae are considered standard candles. Standard candles are light sources that have the same brightness regardless of place and time. The Hubble diagram is commonly used to estimate the value of cosmological parameters. But on the Hubble diagram, the spread of points is quite large. To reduce the scatter of points and to estimate the cosmological parameters more accurately, it will be necessary to standardize the luminosity's of type Ia supernovae. In modern cosmology, the SALT2 model is most often used to standardize the luminosity of supernovae (Guy & et al. (2007)). This model uses two parameters X_1 and C. Where X_1 characterizes the shape of the light curve (describes the stretching of the light curve in time), and the parameter C describes the color of the supernova at maximum brightness. In particular, the distance estimate assumes that supernovae with the same color, shape, and galactic environment have, on average, the same intrinsic luminosity for all redshifts. Given these parameters, the standardization equation can be written as follows:

$$\mu = B_{obs} - (M_B - \alpha X_1 + \beta C)$$

where $\mu = 5 \log D_L(z) + 25$ is the distance modulus, B_{obs} corresponds to the peak apparent magnitude in the B band, and α, β, M_B are the parameters of the standardization equation for distance estimation.

When standardizing the luminosity, it is assumed that the dependence of the decay time of the brightness of supernovae on the maximum brightness, as well as the dependence of the color at the peak on the maximum brightness, do not depend on the age of the predecessor. In Lee & et al. (2022) showed that there is a strong relationship between the parameters α, β and the age of the population of the host galaxy. This dependence lies in the fact that in younger galaxies type 1a supernovae at maximum brightness have a weaker luminosity than supernovae in relatively old galaxies. Since redshift characterizes age on average, the dependence of these parameters on redshift should be observed. Rigault & et al. (2020) studied the star formation rate in

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local environments of type 1a supernovae and found a strong dependence of the standardization parameters on the local star formation rate. In this paper, we study the dependence of standardization parameters on redshift (z) based on some known samples of type Ia supernovae (Kowalski & et al. (2008), Amanullah & et al. (2010), Betoule & et al. (2014)). All data is taken from the authors of these articles, without any changes. It is shown that there is a strong correlation between these parameters and z. We will also discuss what happens if we replace the $(-\alpha X_1 + \beta C)$ term with a redshift dependent term (ϵz).

2. Results

On Fig.1. the dependence of the value $\Delta M = -\alpha X_1 + \beta C$, introduced to standardize the luminosities of type 1a supernovae, on the redshift is shown for the sample of Kowalski & et al. (2008).

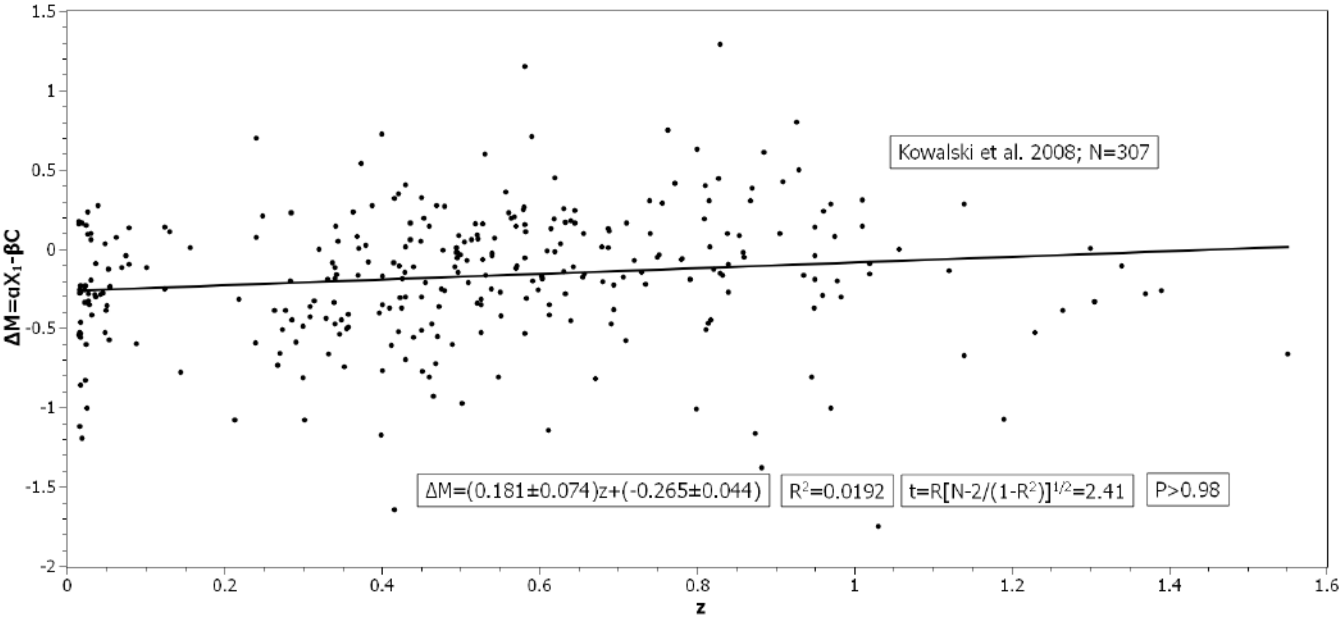

Figure 1. Dependence of the value ΔM introduced for standardization of luminosities of type Ia supernovae on redshift, for the sample of Kowalski & et al. (2008). Correlation significance < 0.02 (2.4σ).

As can be seen from the figure, there is an obvious relationship between the discussed quantities. Let us evaluate the significance of the correlation. For this we will use the value

$$t = \sqrt{(n-2) \div (1-R^2)}$$

which the subject of Student's distribution. Here R the correlation coefficient between the values ΔM and z

We get t=2.41, from which it follows that the significance of the correlation is high $\alpha = 1 - P \approx 0.02$.

On Fig.2. the dependence of the value $\Delta M = -\alpha X_1 + \beta C$ on the redshift is shown, for the sample of Amanullah & et al. (2010). As can be seen, there is a strong correlation at the level of 3.5σ.

On Fig.3. the dependence of the value $\Delta M = -\alpha X_1 + \beta C$ on the redshift is shown, for the sample of Betoule & et al. (2014). There is also a strong correlation at the level of 6.7σ.

For the last sample (Betoule & et al. (2014), we consider the dependence of the parameters αX_1 and βC on the redshift separately.

In Fig.4. The redshift dependence of αX_1, introduced to standardize the luminosity's of type 1a supernovae, is shown for the sample of Betoule & et al. (2014). Significance of correlation > 0.999 (5σ).

In Fig.5. The dependence of the value of βC, introduced to standardize the luminosity's of type 1a supernovae, on redshift is shown for the sample of Betoule & et al. (2014). Significance of correlation > 0.999 (5σ).

Thus, in all studied samples of type 1a supernovae, a strong dependence of the luminosity standardization parameter on the redshift is observed. The correlation is also observed separately for both parameters X_1 and C.

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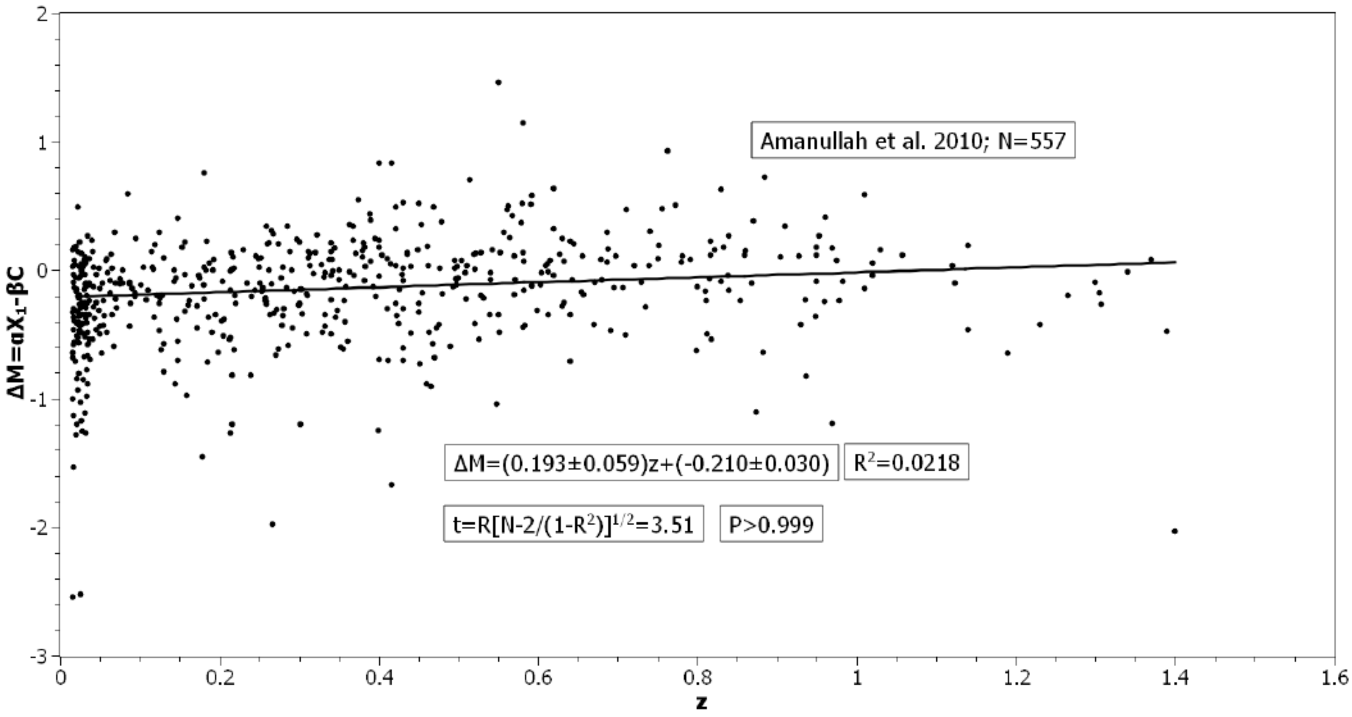

Figure 2. The same as in fig. 2 for a sample of Amanullah & et al. (2010). The correlation is significant at the 3.5σ level.

Such a correlation means that at large z we artificially increase the average absolute magnitude of supernovae during standardization and, therefore, for a given apparent magnitude, on average, we attribute to them a greater distance than they actually have. And so we believe that they are being receding with acceleration.

Thus, we can conclude that such standardization is unsuitable for measuring the distances of type 1a supernovae.

Let's see what happens if we ignore these corrections and estimate the cosmological parameters for the ΛCDM model without standardizing the luminosity's.

We will also try to replace these parameters with a parameter characterizing the evolution of supernovae. We assume that the dependence of the absolute magnitude on the redshift is linear.

For this, we will use observational data from Betoule & et al. (2014), without making any changes to the apparent magnitude B_{obs} of supernovae.

This sample was obtained from a collaboration between SDSS-II (Sloan Digital Sky Survey) and SNLS (SuperNova Legacy Survey) (Betoule & et al. (2014): https://vizier.cds.unistra.fr/viz-bin/VizieR?-source=J/A+A/568/A22).

The collaboration was called JLA - Joint Light curve Analysis. It includes some stars at low redshifts ($z < 0.1$), stars selected from SDSS-II ($0.05 < z < 0.4$) and stars selected from SNLS ($0.2 < z < 1$). A total of 740 spectroscopically confirmed Type Ia supernovae with high-quality light curves.

During the simulation, the authors obtained the following values of the cosmological parameters: $\Omega_M = 0.295; \Omega_\Lambda = 0.705$ (Betoule & et al. (2014)). Let's see what we get.

If we do not take into account evolution, then we will have:

$$M(z) = M_0 = B_{obs} - 5 \log D_L - 25 \tag{1}$$

With the assumption of evolution:

$$M(z) = M_0 + \epsilon z = B_{obs} - 5 \log D_L - 25 \tag{2}$$

where B_{obs} is the apparent magnitude, M_0 is the absolute magnitude at $z = 0$, D_L is the luminosity distance, ϵ is the absolute magnitude evolution coefficient.

Or we can replace the standardization equation with the equation

$$\mu = B_{obs} - (M_0 + \epsilon z) \tag{3}$$

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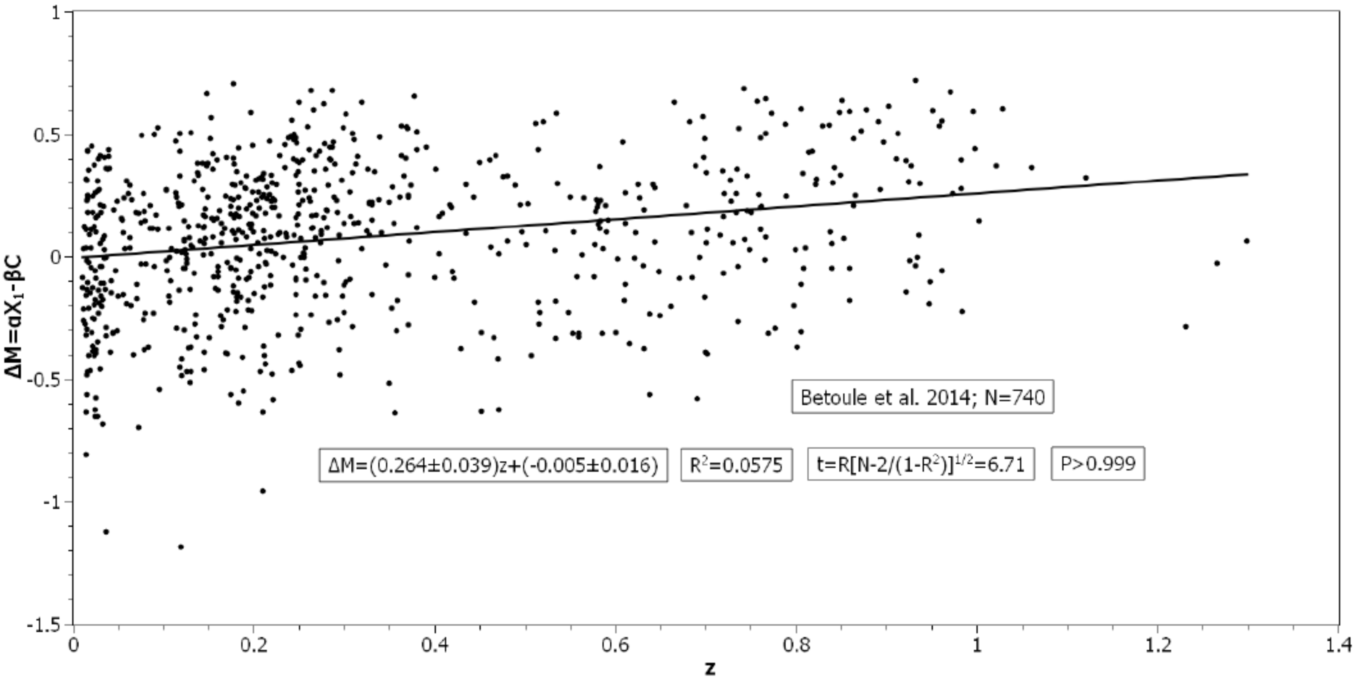

Figure 3. The same as in fig. 2 and 3 for a sample of Betoule & et al. (2014). The correlation is significant at the 6.7σ level.

In the case of the ΛCDM model, the dependence of the luminosity distance on redshift is given by the following formula:

$$D_L(z,\Omega_M,\Omega_\Lambda,\Omega_K) = CH_0^{-1}(1+z)\,|\Omega_K|^{-\frac{1}{2}}\,sinn\left\{|\Omega_K|^{\frac{1}{2}}\int_0^z dz\Big[(1+z)^2(1+\Omega_M z) - z(2+z)\Omega_\Lambda\Big]^{-\frac{1}{2}}\right\} \tag{4}$$

where z is the redshift of the object. H_0 is the Hubble constant (Accepted $H_0 = 72.305\ km.s^{-1}.Mps^{-1}$). Ω_K is related to the curvature of space and in the case of flat universe it is 0 (Carroll & et al. (1992): $\Omega_K = 1-\Omega_M-\Omega_\Lambda$, $sinn = sinh$, when $\Omega_K \geq 0$ and $sinn = sin$, when $\Omega_K \leq 0$. In the case of $\Omega_K = 0$, we will have:

$$D_L(z,\Omega_M,\Omega_\Lambda) = \frac{C(1+z)}{H_0}\times \int_0^z dz\left[(1+z)^2(1+\Omega_M z) - z(2+z)\Omega_\Lambda\right]^{-\frac{1}{2}} \tag{5}$$

or

$$D_L = \frac{C(1+z)}{H_0}\int_0^z dz\left[(1+z)^3\Omega_M + \Omega_\Lambda\right]^{-\frac{1}{2}}$$

If we assume that $\Omega_\Lambda = 1$, and $\Omega_M = 0$, we will have (Weinberg (2008))

$$D_L(z) = \frac{C}{H_0}\left(z+z^2\right) \tag{6}$$

If $\Omega_\Lambda = 0$, and $\Omega_M = 1$, we have

$$D_L(z) = \frac{2C}{H_0}\left[(1+z) - \sqrt{1+z}\right] \tag{7}$$

It should be noted that in 1998, prior to the work of Riess & et al. (1998) and Perlmutter & et al. (1999) commonly used the equations of general relativity (GR) with zero cosmological constant ($\Lambda = 0$). Using this model, Mattig (1958) integrated these equations exactly and obtained the luminosity distance as a function of redshift.

$$D_L(z,q_0) = \frac{C}{H_0 q_0^2}\left[q_0 z + (q_0-1)\left(\sqrt{1+2q_0 z} - 1\right)\right] \tag{8}$$

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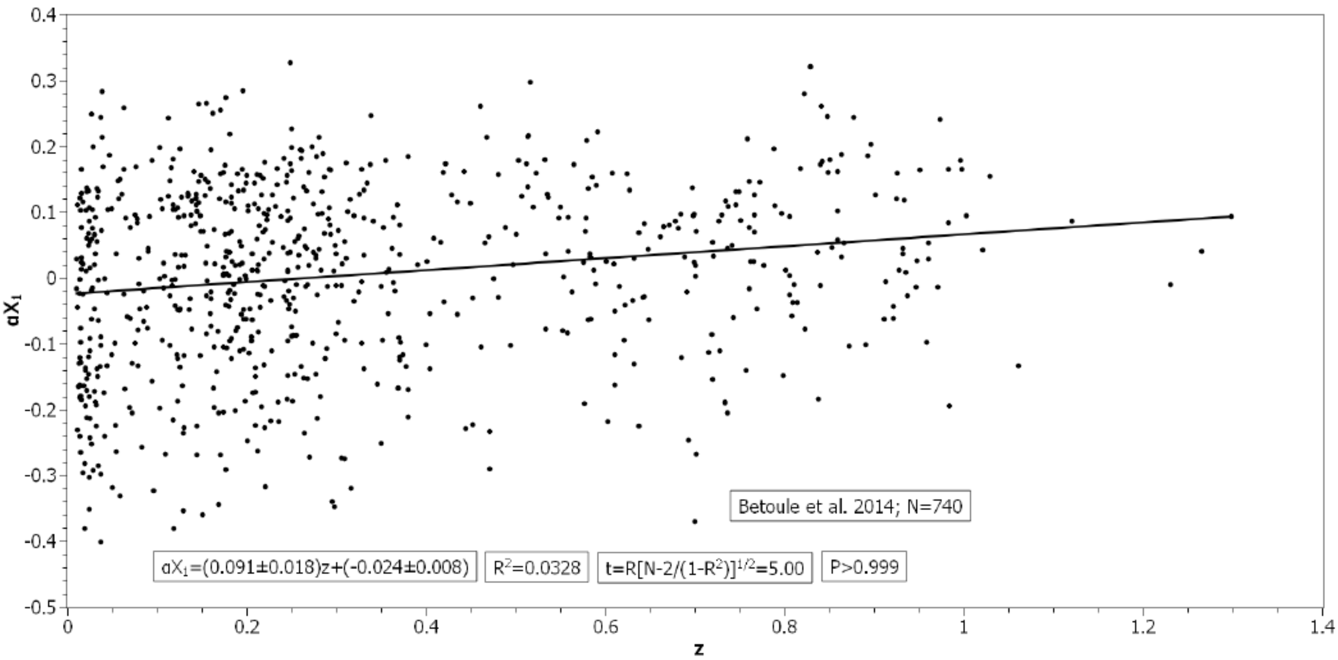

Figure 4. Dependence of the value αX_1 introduced for standardization of luminosity's of type 1a supernovae on redshift, for the sample of Betoule & et al. (2014). Correlation significance < 0.001 (5σ).

Where q_0 is the deceleration parameter, in this case:

$$q_0 = \frac{\Omega_M}{2} \tag{9}$$

(8) with $q_0 = 0.5$ coinciding with (7).

For the luminosity distance in the case of a flat universe we will use formula (5), for the luminosity distance in the model with zero cosmological constant ($\Lambda = 0$) we will use formula (8).

We will also discuss the general case (4) with nonzero space curvature.

On the Hubble diagram, the theoretical curve can be represented by the following relationship:

$$B^{th}_{mag}(z, \Omega_M, \Omega_\Lambda, \Omega_K) = M_0 + \epsilon z + 5\log D_L(z, \Omega_M, \Omega_\Lambda, \Omega_K) + 25 \tag{10}$$

for the Friedmann-Robertson-Walker model, or

$$B^{th}_{mag}(z, q_0) = M_0 + \epsilon z + 5logD_L(z, q_0) + 25 \tag{11}$$

for the model with zero cosmological constant.

We need to find those values of the parameters Ω_M, Ω_Λ, Ω_K, M_0, ϵ in the first case and q_0, M_0, ϵ in the second case, so that the sum of squares $(B^{obs} - B^{th}_{mag}(z))$ would be minimal:

$$Chi^2 = \sum \left(B_{obs} - B^{th}_{mag}(z)\right)^2 = min. \tag{12}$$

In Table. 1. The values of the cosmological parameters of the ΛCDM and CDM models are given under various assumptions about the curvature of space and the evolution of type 1a supernovae for the JLA sample (Betoule & et al. (2014)).

It can be seen from the table that under the assumption of a flat Universe without the evolution of supernova luminosity, we obtain $\Omega_\Lambda = 0.505$, $\Omega_M = 0.495$, but the error in this case is the largest. For a flat Universe, the case with the assumption of the evolution of supernova luminosity's is more acceptable. But then the fraction of dark energy in the Universe turns out to be quite small (almost 0).

If we do not make restrictions on the curvature of space, then we will get a better approximation to the Hubble diagram. In this case, both under the assumption of the absence of evolution of supernova luminosity's and under the assumption of the existence of evolution, the fraction of dark energy turns out to be exactly equal to zero, and the curvature of space turns out to be negative. In this case, the required

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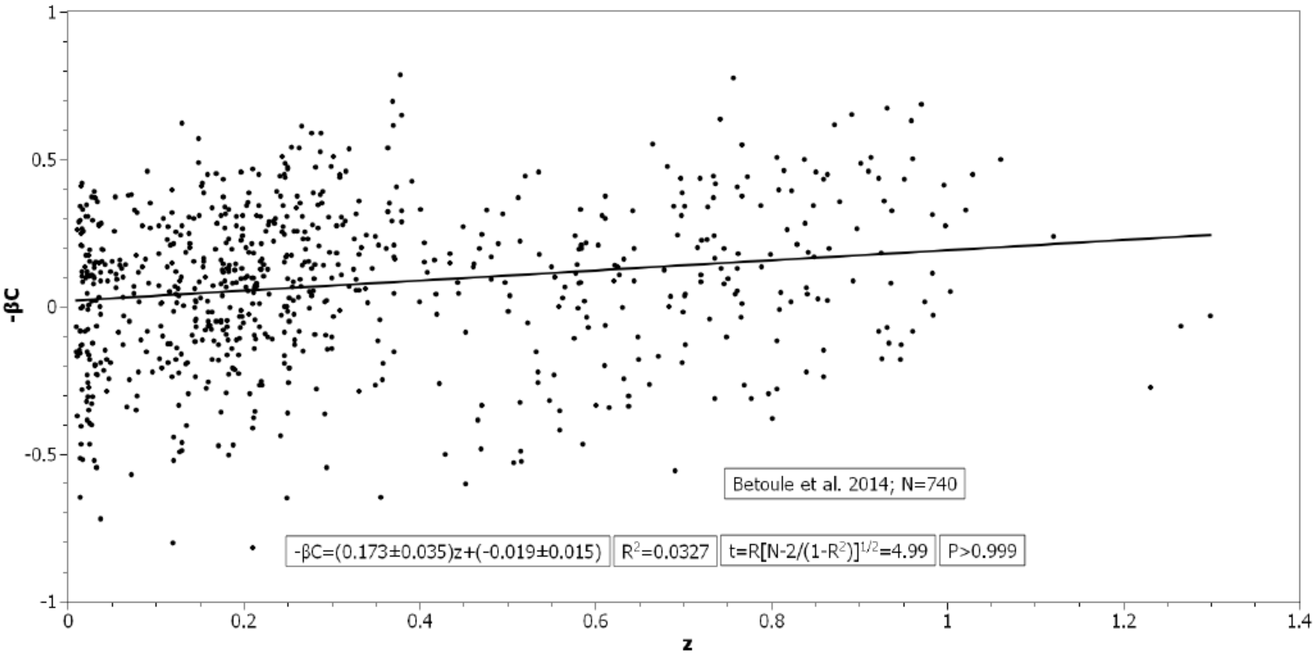

Figure 5. Dependence of the value βC introduced for standardization of luminosity's of type 1a supernovae on redshift, for the sample of Betoule & et al. (2014). Correlation significance < 0.001 (5σ).

Table 1. Values of the cosmological parameters of the ΛCDM and CDM models obtained under various assumptions about the curvature of space and the evolution of type 1a supernovae for the JLA sample (Betoule & et al. (2014)

		Received					
Supposed	Evaluated	M_0	ϵ	Ω_Λ	Ω_M	Ω_K	$< Chi^2 >$
$\Omega_K = 0, \Omega_\Lambda + \Omega_M = 1, \epsilon = 0$	$M_0, \Omega_\Lambda, \Omega_M$	-18.998	-	0.505	0.495	0	0.079493 ± 0.004761
$\Omega_K = 0, \Omega_\Lambda + \Omega_M = 1, \epsilon \neq 0$	$M_0, \epsilon, \Omega_\Lambda, \Omega_M$	-18.961	0.361	0.058	0.942	0	0.079085 ± 0.004756
$\Omega_\Lambda + \Omega_M + \Omega_K = 1, \epsilon = 0$	$M_0, \Omega_\Lambda, \Omega_M, \Omega_K$	-18.960	-	0.000	0.216	0.784	0.079046 ± 0.004755
$\Omega_\Lambda + \Omega_M + \Omega_K = 1, \epsilon \neq 0$	$M_0, \epsilon, \Omega_\Lambda, \Omega_M, \Omega_K$	-18.959	-0.044	0.000	0.146	0.854	0.079045 ± 0.004755
Supposed	Evaluated	M_0	ϵ		q_0		$< Chi^2 >$
$\Lambda = 0, \epsilon = 0$	M_0, q_0	-18.960	-		0.108		0.079046 ± 0.004755
$\Lambda = 0, \epsilon \neq 0$	M_0, ϵ, q_0	-18.959	-0.044		0.073		0.079045 ± 0.004755

evolution is small. True, if we assume evolution, then we will get a somewhat small value of Chi^2, but we cannot give preference to what.

The last two lines show the simulation results for the Universe model with zero cosmological parameter. Thus, the best approximation of the Hubble diagram for the ΛCDM model is the same as the best approximation of the CDM model. That is, the model with zero cosmological constant describes the Universe no worse than the ΛCDM model.

Let's see how good these approximations are for the entire studied redshift interval.

On Fig. 6-9 show the residuals of the observational data (the difference between the observed and theoretical apparent magnitudes) as a function of redshift.

In all figures, a horizontal line is obtained, almost indistinguishable from the line $B_{obs} - B_{th} = 0$. It means that

1. The ΛCDM model describes the Universe well.

2. The observational data have been fairly well processed by the JLA authors over the entire redshift range.

Let's try to see what happens if we take $\epsilon = -0.264$ in the formula $\mu = B_{obs} - (M_0 + \epsilon z)$ (based on the obtained dependence $\Delta M = \alpha X_1 - \beta C = 0.264z - 0.005$ in Fig. 3) and estimate the cosmological parameters.

It turns out $\Omega_\Lambda = 0.73$, $\Omega_M = 0.27$, $M = -19.013$. That is, approximately what is obtained in many studies by standardizing supernovae according to the formula $\mu = B_{obs} - (M_B - \alpha X_1 + \beta C)$.

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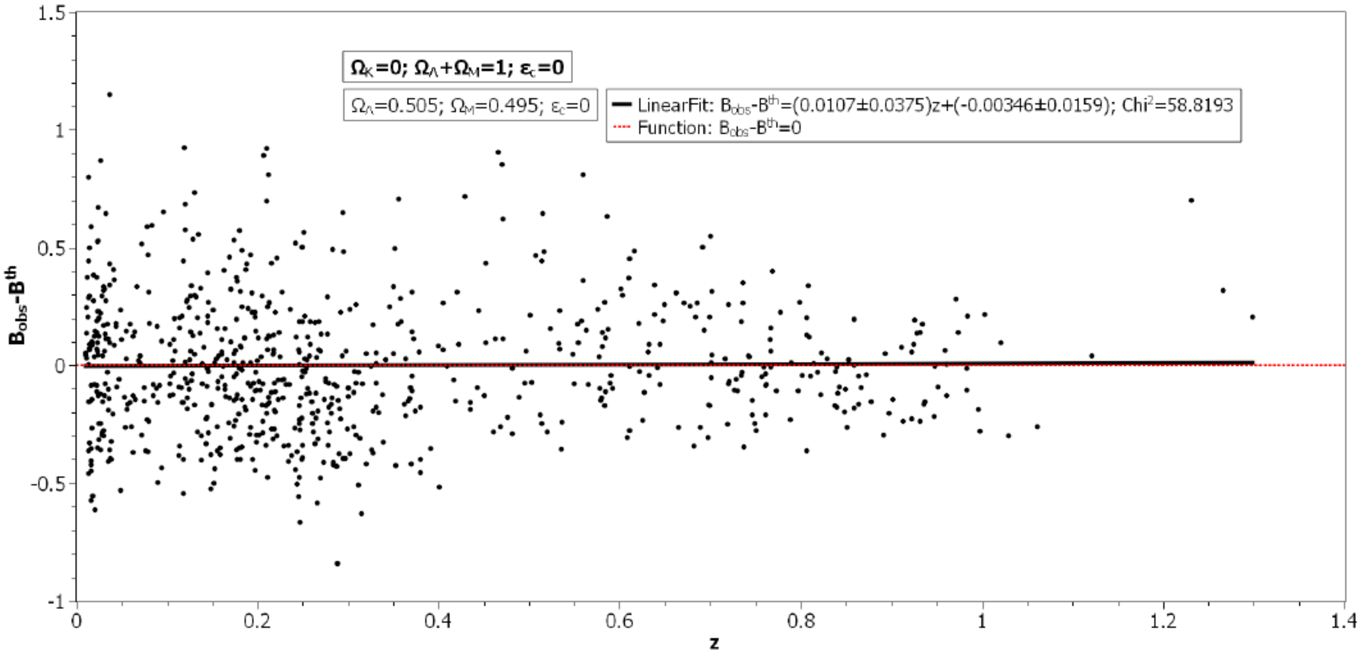

Figure 6. The difference between the observed and theoretical apparent magnitudes from the redshift for the case $\Omega_K = 0, \Omega_\Lambda + \Omega_M = 1, \epsilon = 0$.

3. Conclusion

The standardization of light curves for type 1a supernovae was invented in order to minimize the errors and bring the observational data on the Hubble diagram closer to the theoretical ones and to obtain the constraint on the cosmological parameters as accurately as possible. As a result, a close fit between observations and theory has been obtained (eg, Betoule & et al. (2014)). But, in our opinion, the authors of these works made a serious systematic error.

This leads to the fact that at large z we artificially increase the average absolute magnitude of supernovae during standardization and, therefore, for a given apparent magnitude, on average, we attribute to them a greater distance than they actually have. And so we believe that they are being receding with acceleration.

Therefore, we can conclude that such standardization is unsuitable for determining the cosmological parameters.

To determine the cosmological parameters, we study two options:

1. Do not standardize, i.e. use the apparent magnitudes of supernovae without any corrections.

2. For standardization, we assume that the absolute magnitudes of type 1a supernovae depend on the redshift and instead of the standardization relation

$$\mu = B_{obs} - (M_B - \alpha X_1 + \beta C)$$

use relation

$$\mu = B_{obs} - (M_B + \epsilon z)$$

The following results are obtained:

• Assuming a flat Universe without supernova luminosity evolution, we obtain $\Omega_\Lambda = 0.505, \Omega_M = 0.495$, but the error in this case is the largest. For a flat Universe, the case with the assumption of the evolution of supernova luminosity's is more acceptable. But then the share of dark energy in the Universe turns out to be quite small (almost 0). For the evolution coefficient, we obtain $\epsilon = 0.361$.

• If we do not impose restrictions on the curvature of space, we will get a better approximation to the Hubble diagram. In this case, both under the assumption of the absence of evolution of supernova luminosity's and under the assumption of the existence of evolution, the fraction of dark energy turns out to be exactly equal to zero, and the curvature of space turns out to be negative. In this case, the required evolution is small and can even be neglected. True, if we assume evolution, then we get a somewhat small value of Chi^2, but the difference in Chi^2 is so small that we cannot give preference to it.

In one case we get

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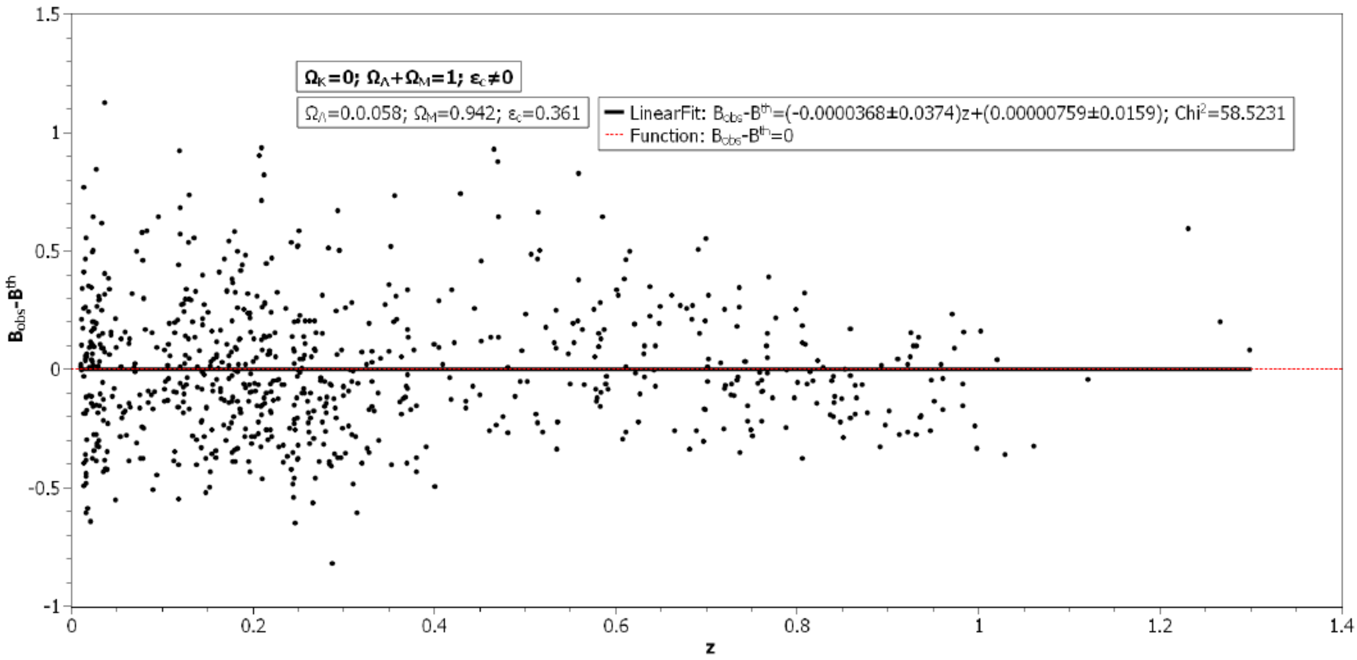

Figure 7. The difference between the observed and theoretical apparent magnitudes from the redshift for the case $\Omega_K = 0, \Omega_\Lambda + \Omega_M = 1, \epsilon \neq 0$.

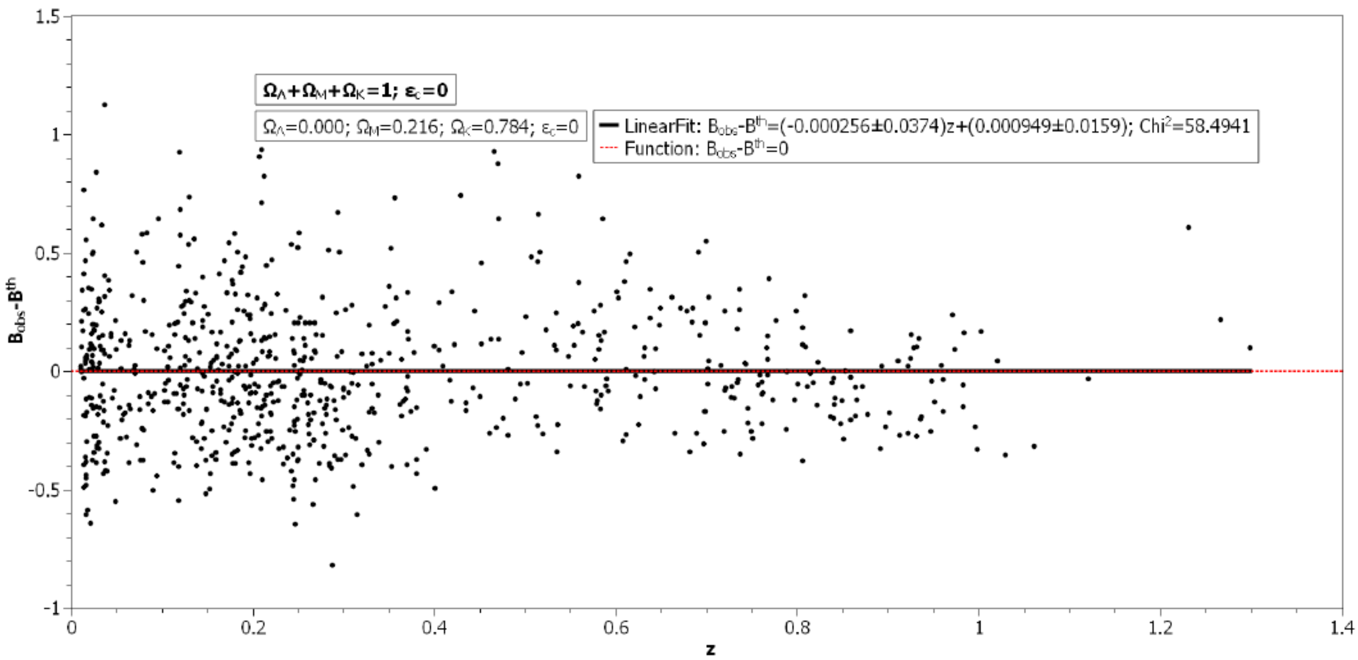

Figure 8. The difference between the observed and theoretical apparent magnitudes from the redshift for the case $\Omega_\Lambda + \Omega_M + \Omega_K = 1, \epsilon = 0$.

$\Omega_\Lambda = 0.000$, $\Omega_M = 0.216$, $\Omega_K = 0.784$, $\epsilon = 0$, (analogue for the CDM model is $q_0 = 0.108$)
otherwise we get
$\Omega_\Lambda = 0.000$, $\Omega_M = 0.146$, $\Omega_K = 0.854$, $\epsilon = -0.044$, (analogue for the CDM model is $q_0 = 0.073$).

From the above analysis, we can conclude that the reason for the result about the existence of dark energy lies in the incorrect standardization of supernova luminosity's. Apparently dark energy doesn't exist.

Evidence of the evolution of the luminosity's of type 1a supernovae and the probable absence of dark energy was also obtained in our other papers and reports Mahtessian & et al. (2020), Mahtessian & et al. (2021), Mahtessian & et al. (2022), Mahtessian & et al. (2023)), as well as by other authors (for example, Kang & et al. (2020)).

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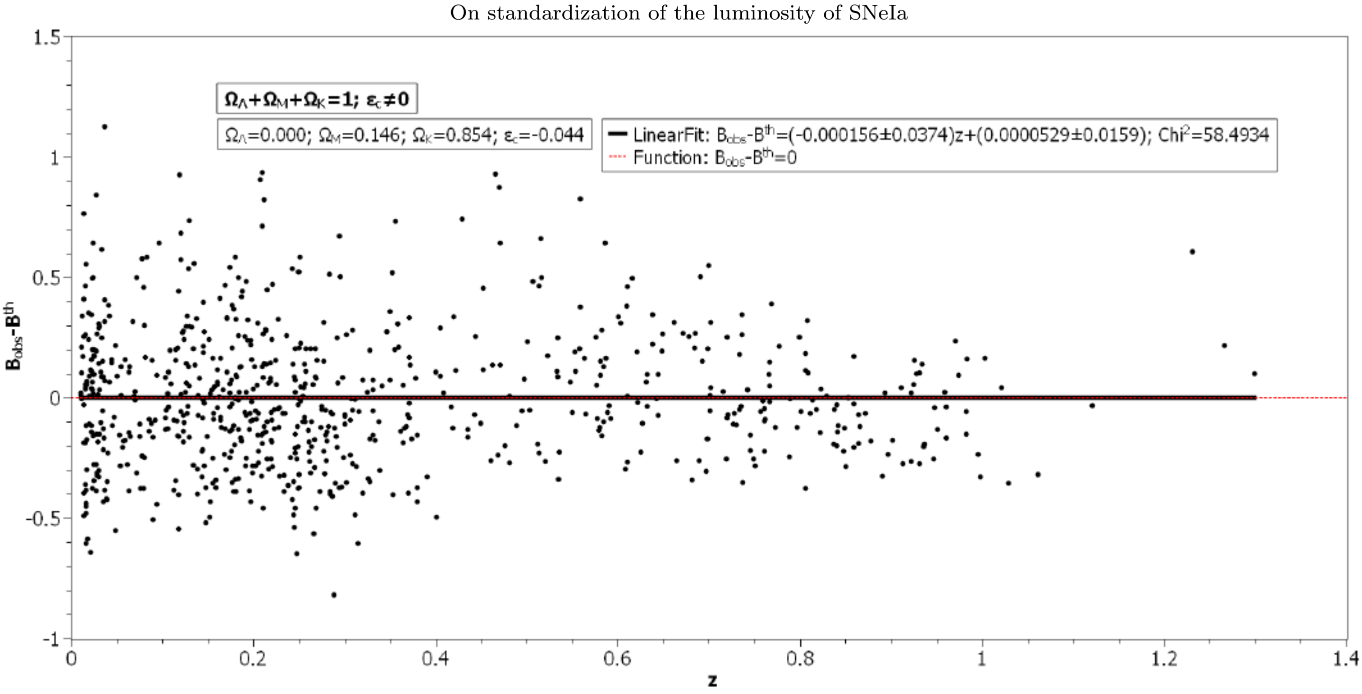

Figure 9. The difference between the observed and theoretical apparent magnitudes from the redshift for the case $\Omega_\Lambda + \Omega_M + \Omega_K = 1, \epsilon \neq 0$.

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