Modification of the method for measuring the CMB temperature based on the Sunyaev–Zeldovich effect

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Independent measurements of the cosmic microwave background (CMB) temperature T_0 in the modern era using cosmological data are extremely important for the verification of cosmological models. In this paper, the standard and new procedures for measuring the cosmic microwave background temperature in the method of the Sunyaev–Zeldovich effect were investigated. The work was performed using numerical simulation of an artificial catalog of observations of the Sunyaev–Zeldovich effect for clusters. As a result, it was found out that a new procedure described in the work provides a more accurate assessment. It is also shown that the reason for the discrepancy in the procedures is the uncertainty of the pecular velocity parameter β, which is part of the Sunyaev–Zeldoich effect.

Keywords: Cosmic microwave background, CMB, cosmology, Sunyaev–Zeldovich effect.

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Introduction

The spectrum of cosmic microwave background „here" and „now" with high precision is close to the spectrum of an absolute black body with temperature $T_0 = 2.7255 \pm 0.0006$ K [1]. Dynamics of temperature in process of Universe development is described by the dependence of this value on the cosmological red shift z. In the standard cosmological ΛCDM-model this dependence looks like

$$T_z = T_0(1 + z). \tag{1}$$

However, it has a different appearance in the alternative cosmological models going beyond the standard physics. Therefore, its most precise measurements are extremely important for research of the Universe laws.

Currently there are two methods known and implemented for the measurement of the temperature of the cosmic microwave background (CMB) T_z at z: one uses the Sunyaeva–Zeldovich effect (SZ-effect) [2,3], the second one — analysis of occupation of the energy levels in atoms and molecules in dense interstellar clouds [4].

This paper studied the standard procedure and the procedure proposed below in the method of SZ-effect with the help of the numerical modeling of the artificial catalog of SZ-effect modeling.

1. Method of study

This paper used the following approach. Firstly, the artificial catalog of SZ-effect measurements was modeled numerically in the galaxy clusters, parameters (necessary for the effect) of which were generated randomly, and the CMB temperature value „here" and „now" was assigned the value $T_0 = 2.7255$ K. Secondly, the assigned value was assessed using the two procedures. Comparison of the produced estimates with the CMB temperature set in modeling made it possible to study the procedures.

1.1. SZ-effect. Measurement procedures

SZ-effect consists in shifting the CMB spectrum from the spectrum of the absolute black body (ABB) when the relict photons pass through the hot electron gas in the galaxy cluster. The effect may be described as a variation of CMB intensity $\Delta I_{SZ}(\nu)$ at frequency ν and as a variation of brightness temperature of CMB $\Delta T_{SZ}(\nu)$. The effect depends on frequency ν and four parameters: T — CMB temperature, τ — optical thickness, $\beta = v/c$ — peculiar velocity of the cluster, $\theta = kT_e/m_ec^2$ — temperature of electron gas in the electron rest energy units.

The standard procedure of CMB temperature measurement T_z in the cosmological red shift z by SZ-effect consists in the approximation of the CMB temperature variations ΔT_{SZ} at different frequencies using formula (2):

$$\begin{aligned} &\Delta T_{SZ}(x) = T_0 \cdot \tau\ [\theta f(x) - \beta + R(x, \theta, \beta)] \\ &x = h\nu_0(1+z)/kT_z, \qquad \xrightarrow{\text{fitting}} (T_z, \tau, \theta, \beta), \\ &T_0 = 2.7255\text{K [1]}, \end{aligned} \tag{2}$$

where functions $f(x)$ and $R(x, \theta, \beta)$ are described in paper [2]. In this procedure the CMB temperature T_z is found in the cosmological red shift z. Such procedure was used in papers [2,3]. In these papers the main objective was to determine the statistically significant deviation of the values $T_z(z)$ from ΛCDM-model by approximation with the function differing from the standard one (1). Paper [4] proposed a different method to determine the data deviation, namely by finding the estimate of the CMB temperature RI „here“ and „now“ T_0 through the approximation of the values T_z by the function from the standard model (1) and its comparison to the best estimate of today in [1]. Therefore, the result of the standard procedure is the estimation of the CMB temperature „here“ and „now“ T_0.

This paper proposes the new procedure, which makes it possible to immediately find the value of CMB temperature T_0 „here“ and „now“. In this procedure the approximation of the CMB temperature ΔT_{SZ} variations is carried out using formula (3):

$$\begin{aligned}&\Delta T_{SZ}(x) = T_0 \cdot \tau \, [\theta f(x) - \beta + R(x, \theta, \beta)] \\ &x = h\nu_0 / kT_0,\end{aligned} \xrightarrow{\text{fitting}} (T_0, \tau, \theta, \beta), \tag{3}$$

where functions $f(x)$ and $R(x, \theta, \beta)$ are the same as in formula (2). The important difference of the new procedure from the standard one consists in the fact that in the new procedure prior to the optical thickness τ there is a varied parameter (the sought CMB temperature „here“ and „now“), and the standard one includes temperature equated to the average value from paper [1].

1.2. Numerical modeling of the artificial catalog

Numerical modeling of artificial catalog of SZ-effect for the clusters was carried out as follows. First, the CMB temperature value was recorded $T_0 = 2.7255$ K, which had to be recovered by the two above procedures. Second, the parameters of clusters (τ, θ, β, z) were generated randomly from the following distributions. The optical thickness τ was selected from the even distribution $U[0.5, 2]$. Electron gas temperature kT_e, determining parameter θ, — from $U[1, 10]$ keV. Peculiar velocity β — from $U[-0.5/300, +0.5/300]$. Red shift z was taken as module $|\xi|$, where the random value ξ was selected from the normal distribution $N(0, 0.3^2)$. Third, using formula (3), the temperature variations were calculated at five frequencies for each cluster: 70, 100, 143, 217, 353 GHz (as in paper [2]). Fourth, the statistical analysis was made on the errors of real data from papers [2], which defined the correlation between the value of the temperature variation error and frequency (see table). Finally, values spread around the calculated variations of temperatures using the normal law with the dispersions corresponding to the statistical analysis were entered in the catalog. Besides, the catalog included all parameters (τ, θ, β, z) for each cluster. The production of the data entered into the artificial catalog is additionally described in fig. 1.

Result of statistical data analysis from paper [2]

ν, GHz	70	100	143	217	353
$\delta =$ mistake/scale	0.5	0.14	0.07	0.06	0.3
$\sigma = \sqrt{D[\delta]}$	0.09	0.03	0.02	0.02	0.08

Note. $D[\delta]$ — dispersion of value δ.

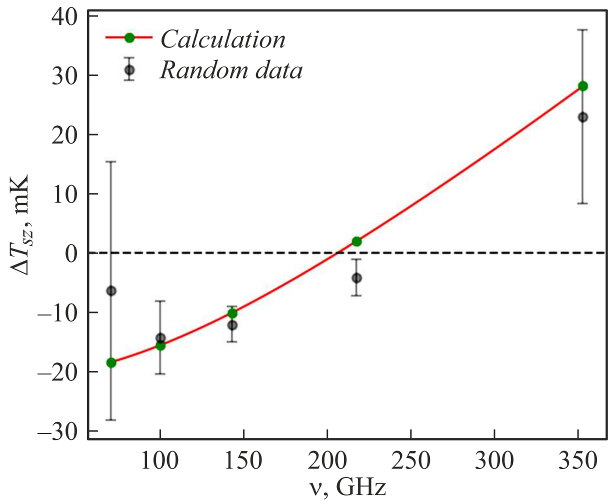

Figure 1. Curve of temperature variations for one cluster with parameters $kT_e = 1.6$ keV, $\beta = 6.2 \cdot 10^{-4}$, $\tau = 1.4$ and $z = 0.3804$. Using these parameters in formula (3), the temperature variations were calculated at frequencies 70, 100, 143, 217, 353 GHz (green dots on the curve). Data (black dots with errors), recorded in the artificial catalog, were generated from the normal distribution with average values in the green dots and dispersions produced from statistical analysis of real errors in the measurements of temperature variations in paper [2].

1.3. Catalog analysis

Using the artificial data (temperature variations), the approximation was carried out, according to the above procedures. The standard procedure determined the set of the temperature values T_z at different cosmological red shifts z for different clusters from the catalog. The value T_0 was found by approximation of this set using the standard law $T_z = T_0(1 + z)$. The new procedure produces the set of temperature values T_0, which was averaged.

All approximations and averagings were made by Monte Carlo method using the scheme of Markovian networks [5]). This method uses the Bayes' theorem, for which it is necessary to set the a priori functions of distribution for each approximating parameter. If there is no information about any approximating parameter, the a priori function for that parameter would be the homogeneous function of distribution $U[a, b]$ (see [6]). This paper assumed that the a priori information about the approximating parameters τ, β, T_0 was absent, in contrast to the parameter θ. Paper [2] used for parameter θ the additional measurements from other papers and other estimates. In our paper the a

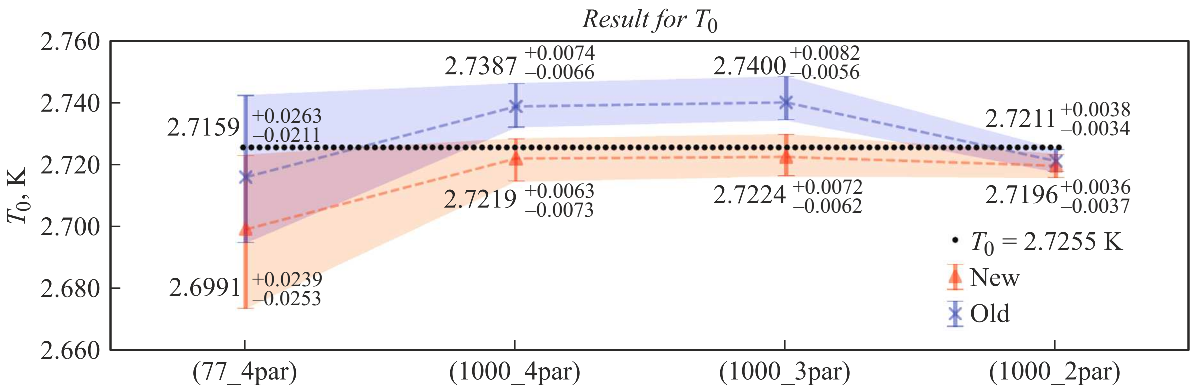

Figure 2. Estimates of cosmic microwave background temperature T_0 by various procedures and different approximation methods. Blue means a standard procedure. Red — a new procedure. Dots with absciss „(77_4par)" — processed 77 clusters with four free approximating parameters; dots with „(1000_4par)" — processed 1,000 clusters with four free parameters; with absciss „(1000_3par)" — processed 1,000 clusters with three free parameters (electron gas temperature θ is recorded); „(1000_2par)" — processed 1,000 clusters with two free parameters (recorded θ and peculiar velocity β). A black dotted line — the value of the CMB temperature of the radiation that had to be recovered.

priori function of this parameter distribution was a normal function of distribution $N(\theta_0, (0.01\theta_0)^2)$, where θ_0 — the actual value of the electron gas temperature, which was known in advance during catalog modeling.

The Monte Carlo method using the scheme of Markovian networks was implemented in Python programming language using emcee and chainconsumer libraries.

2. Results

As a result, a catalog was created of 1,000 clusters: 1,000 sets of parameters (τ, θ, β, z) were generated. From this catalog the two procedures were used to first process 77 clusters (as in paper [2]). With such sample volume the procedures provide the statistically indistinguishable estimates of CMB temperature (fig. 2), the first pair of red-blue dots). When the entire catalog is processed, the procedure provide a systemic shift in the CMB temperature estimation by more than 2σ, besides, the new procedure recovers value $T_0 = 2.7255$ K within 2σ, and the standard procedure — will not.

To find out the cause for the difference in the estimates of the CMB temperature produced by various procedures, the processing of the entire catalog was repeated for the smaller quantity of the approximating parameters. First, for the repeated processing of the entire catalog for each cluster, a value was assigned to parameter $\theta = kT_e/m_ec^2$ as recorded in the catalog, which reduced the number of the free parameters. The result is given in fig. 2 (the third pair of the red-blue dots). This did not reduce the shift in the CMB temperature estimates. Then the catalog was processed once again, but in addition the parameter β was fixed peculiar velocity of the cluster (see fig. 2, the fourth pair of red-blue dots). The statistically significant difference in the CMB temperature estimates was cleared. Accordingly, one may conclude that the systemic shift occurs due to the absence of the a priori information on parameter β.

Conflict of interest

The authors declare that they have no conflict of interest

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