Estimation of the Cosmic Microwave Background Temperature from Atomic CI and Molecular CO Lines in the Interstellar Medium of Early Galaxies

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Abstract—The linear increase of the cosmic microwave background (CMB) temperature with cosmological redshift, $T_{\text{CMB}} = T_0(1 + z)$, is a prediction of the standard cosmological ΛCDM model. There are currently two methods to measure this dependence at redshift $z > 0$ and, what is equally important, to estimate of the CMB temperature $T_0$ at the present epoch. The first method is based on the Sunyaev–Zeldovich effect for a galaxy cluster. However, this method is limited to redshifts $z \lesssim 1$ and only the deviations from the standard relation can be measured with it. The second method is based on the analysis of the populations of atomic and molecular energy levels observed in the absorption spectra of quasars. This method allows $T_{\text{CMB}}(z)$ to be measured directly. We present new estimates of $T_{\text{CMB}}(z_i)$ in the redshift range $1.7 \leq z_i \leq 3.3$ based on the analysis of the excitation of CO rotational levels and CI fine-structure levels in 15 absorption systems. We take into account the collisional excitation of CO and CI with hydrogen atoms and H$_2$ and the radiative pumping of CI by the interstellar ultraviolet radiation. Applying this corrections leads to a systematic decrease in the previously obtained estimates of $T_{\text{CMB}}(z_i)$ (for some systems the magnitude of the effect is $\sim 10\%$). Combining our measurements with the measurements of $T_{\text{CMB}}(z)$ in galaxy clusters we have obtained a constraint on the parameter $\beta = +0.010 \pm 0.013$, which characterizes the deviation of the CMB temperature from the standard relation, $T_{\text{CMB}} = T_0(1 + z)^{1-\beta}$, and an independent estimate of the CMB temperature at the present epoch, $T_0 = 2.719 \pm 0.009$ K, which agrees well with the estimate from orbital measurements, $T_0 = 2.7255 \pm 0.0006$ K.

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INTRODUCTION

Having been born in the first instants of the Big Bang, the cosmic microwave background (CMB) plays a crucial role in the post-inflation expansion dynamics of the Universe at the early stage of its evolution. Within fractions of a second after the completion of the inflationary stage, the Universe passes to the radiation-dominated stage, during which its expansion rate is determined by relativistic matter (mostly photons and neutrinos) whose energy density is much greater than the energy of all other forms of matter (baryonic matter, dark matter, and dark energy). Only approximately 50 000 years after the Big Bang (see, e.g., Gorbunov and Rubakov 2016) does nonrelativistic matter (dark matter and baryons) begin to dominate in the energy density and to change the expansion rate of the Universe, transferring it to the stage of dominance of nonrelativistic matter.

Apart from the expansion dynamics of the Universe, the CMB plays a crucial role in two physical processes that are cosmological markers in the evolution of the Universe. These are primordial nucleosynthesis, which began approximately 180 s (3 min) after the Big Bang and lasted slightly more than three hours, and primordial hydrogen–helium plasma recombination, which proceeded 380 000 years after the Big Bang. Both these processes proceed at dis-

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1 The processes that determined the initial conditions for primordial nucleosynthesis—neutrino decoupling, electron–positron annihilation, and a decrease in the neutron fraction—proceeded slightly earlier, 0.1 s after the Big Bang.
tinctly different cosmological epochs, nuclear physics in the first case and atomic physics in the second case are used for their description, for each of them there are observational data that provide independent estimates for the key cosmological parameters.

At present, three key properties of the CMB attract particular attention, because their study gives important cosmological information. These include (i) the direct Planck blackbody spectrum (Fixsen et al. 1996) and its distortions, (ii) the angular CMB temperature anisotropy (Planck Collaboration 2020), and (iii) the CMB polarization whose studies can lead to the detection of primordial gravitational waves. Yet another important prediction of the standard cosmological model is the dependence of the CMB temperature on cosmological redshift $z$:

$$T_{CMB} = T_0(1 + z),$$

where $T_0 = 2.7255 \pm 0.0006$ K is the current CMB temperature (Fixsen 2009). In such a form this relation has held from the epoch of the primordial nucleosynthesis until now. Its validity has been tested with numerous observations, consistent with the theory of primordial nucleosynthesis and primordial recombination; however, as yet there are no direct observations confirming this relation for these epochs. Furthermore, there are various alternative cosmological models which predict a deviation of the redshift dependence of the CMB temperature from the standard relation (see, e.g., Freese et al. 1987; Matyjasek 1995).

In this paper we focus on the possibility of testing the standard law of evolution of the CMB temperature and on the methods for an independent estimation of the current CMB temperature $T_0$.

**CMB TEMPERATURE MEASUREMENTS**

Observational indications of the CMB were detected long before the prediction of this phenomenon itself by Gamow and Alpher and Herman (1946, 1948). While studying the CN molecules in the interstellar medium (ISM) of our Galaxy, McKellar (1940) found that not all of the CN molecules are in the ground energy state (as was originally assumed for a diffuse cold medium) and some of the molecules are in an excited state as if they were excited by thermal radiation with a temperature $T \sim 3$ K. Only much later, when Penzias and Wilson (1965) discovered the CMB radiation, did it become clear that this radiation permeates the entire space and excites molecules. Roth and Meyer (1993) performed more accurate measurements of the excitation of CN molecules in the ISM of our Galaxy and obtained an estimate, $T_0 = 2.729^{+0.023}_{-0.031}$ K, that agrees well with the currently most accurate estimate from the COBE/FIRAS and WMAP space experiments: $T_0 = 2.7255 \pm 0.0006$ K (Fixsen 2009). However, these CMB temperature measurements were performed “here” and “now,” i.e., in the Solar System and at the present epoch ($z = 0$). There are currently two methods to measure the CMB temperature at redshift $z > 0$.

The first method is based on the analysis of the Sunyaev–Zeldovich (SZ) effect for galaxy clusters (Zeldovich and Sunyaev 1969) and was proposed 10 years after the prediction of the SZ effect by Fabbri et al. (1978) and Rephaeli (1980). Despite the fact that the galaxy clusters are at different cosmological redshifts $z_i$, the distortion of the CMB spectrum caused by the interaction of CMB photons with a hot electron gas is $z$-independent within the standard cosmological model. This is because the dependence of both the Planck spectrum and its distortion caused by the SZ effect on frequency $\nu$ is defined via the dimensionless parameter $x$,

$$x = \frac{h \nu(z_i)}{kT(z_i)} = \frac{h \nu_0(1 + z_i)}{kT_0(1 + z_i)} = \frac{h \nu_0}{kT_0},$$

which is $z$-independent within the standard cosmological model, where the change in photon frequency and CMB temperature is proportional to the same factor $(1 + z)$. However, within alternative cosmological scenarios the SZ distortions of the Planck spectrum can become $z$-dependent. The deviations of the evolution of the CMB temperature from the standard relation (1) can be parametrized in the form proposed by Lima et al. (2000):

$$T(z) = T_0(1 + z)^{1-\beta},$$

while the redshift dependence of the frequency, being a more general property defined by General Relativity, $\nu(z) = \nu_0(1 + z)$ does not change. This leads to the $z$ dependence of the spectral shape of the SZ distortion due to the $x(z)$ dependence:

$$x = \frac{h \nu_0(1 + z_i)}{kT_0(1 + z_i)^{1-\beta}} = \frac{h \nu_0}{kT_0}(1 + z)^{\beta}.$$  

This underlies the method of searching for possible deviations from the standard relation (1). Moreover, within both the standard and alternative theories the SZ effect allows (as was pointed out by Fabbri et al. (1978) and Rephaeli (1980)) the current CMB temperature $T_0$ to be independently estimated owing to the spectral peculiarities of the SZ distortion. In particular, there exists a critical value of the dimensionless parameter $x_0 = 3.830$ for which the distortion of the Planck spectrum is zero. Thus, if we measure the wavelength $\lambda_0$ at which the distortion of the Planck spectrum toward a galaxy cluster is zero, then we can determine the $T_0 = h\nu/(3.830k\lambda_0)$ to be also measured (Fabbri et al. 1978).
In recent years, in view of the increase in observational statistics, many studies have been performed to test the standard evolution of the CMB temperature (see, e.g., Battistelli et al. 2002; Luzzi et al. 2009; Hurier et al. 2014; Luzzi et al. 2015; Avgoustidis et al. 2016). In our paper we will also use data on the SZ effect.

The second method is based on the analysis of the excitation of atomic and molecular energy levels observed in the absorption spectra of quasars. It was proposed even earlier than the first method, by Bahcall and Wolf (1968). This method allows $T_{\text{CMB}}(z)$ to be measured directly (see, e.g., Srianand et al. 2000). The most convenient elements in this method are the fine-structure energy levels of atomic C I and the rotational levels of CO molecules (Silva and Viegas 2002; Srianand et al. 2008; Noterdaeme et al. 2011).

Each of the described methods has its advantages and disadvantages. The $T_{\text{CMB}}(z)$ measurements in galaxy clusters have high statistics of the number of systems, but they are limited to the redshift range $z \leq 1$, for which the deviation of $T_{\text{CMB}}(z)$ from the standard relation is small. In contrast, the $T_{\text{CMB}}(z)$ measurements using the analysis of atomic and molecular absorption lines correspond to redshifts $z \sim 2–3$, at which the possible deviation from the standard relation can be more significant. However, the probability to detect molecular systems in the spectra of quasars is rather low, $\sim 4\%$ (Balashev and Noterdaeme 2018) due to the molecular clouds being compact (for example, in comparison with atomic absorption clouds). Second, this method requires quasar spectra with a high signal-to-noise ratio and a high spectral resolution. At present, CO absorption lines at $z \sim 2$ have been detected in six quasar spectra (Noterdaeme et al. 2011, 2018) and about 20 C I absorption systems at $z = 2–3$ have been detected in high-resolution quasar spectra. The main source of the systematic effects is related to the uncertainty of the physical conditions in absorption systems, which often cannot be measured well. Therefore, only upper limits on $T_{\text{CMB}}(z)$ have been set for most C I absorption systems. Klimenko and Balashev (2020) showed that a consistent analysis of the excitation of C I fine-structure levels and H$_2$ rotational levels allows the physical conditions (UV background intensity, gas number density, the kinetic temperature) in absorption systems to be determined more reliably.

In conclusion of this section, note once again that both these methods allow one to independently estimate the current CMB temperature $T_0$, that was proposed in early papers and which is occasionally overlooked later. This can be done by extrapolating the dependence $T(z)$ to zero redshift ($z = 0$), i.e., by considering $T_0$ as a free parameter when fitting the data with the relation $T(z) = T_0(1 + z)^{1-\beta}$ (for $\beta = 0$ and $\beta \neq 0$).

An increase in statistics on galaxy clusters and absorption systems will potentially allow $T_0$ to be determined with an accuracy comparable to or even better than what is done “here” and “now.”

In this paper we present our new measurements of $T_{\text{CMB}}(z)$ in C I and CO absorption systems with $z > 1.7$ made by applying the correction for collisional (for C I and CO) and radiative pumping by interstellar UV radiation (for C I) and an independent estimate of the current CMB temperature $T_0$.

### OBSERVATIONAL DATA

To measure the CMB temperature, we select 15 damped Lyman-α absorption systems (DLAs) with high redshifts $z > 1.7$ that have high molecular hydrogen column densities ($\log N(\text{H}_2) > 18$) and associated C I absorption lines. There are CO absorption lines in six DLAs (Noterdaeme et al. 2011, 2018). A list of the systems is presented below in Tables 2 and 3. The observations were performed with the high-resolution spectrographs UVES (Dekker et al. 2000) at the ESO VLT-UT2 telescope in Chile and HIRES (Vogt et al. 1994) at the Keck telescope in Hawaii. The parameters of the observations and the primary analysis of the spectra are described in Noterdaeme et al. (2018) (J0000+0048), Klimenko et al. (2015) (B0528−2508), Balashev et al. (2010) (for J0812+3208, Keck), Guimaraes et al. (2012) (J0816+1446), Balashev et al. (2017)(J0843+0221),

| Parameter | J0857+1855 | J1047+2057 | J1705+3543 |
|-----------|------------|------------|------------|
| $z$        | 1.7293     | 1.7738     | 2.0377     |
| $\log N(\text{C I})$ | 13.96$^{+0.10}_{-0.10}$ | 14.57$^{+0.06}_{-0.06}$ |           |
| $\log N(\text{C I}^*)$ | 13.67$^{+0.08}_{-0.08}$ | 14.49$^{+0.05}_{-0.05}$ |           |
| $\log N(\text{C I}^{* *} )$ | 13.25$^{+0.07}_{-0.07}$ | 13.98$^{+0.05}_{-0.05}$ |           |
| $\log N(\text{CO}, J = 0)$ | 13.08$^{+0.08}_{-0.08}$ | 14.53$^{+0.21}_{-0.21}$ | 13.46$^{+0.06}_{-0.06}$ |
| $\log N(\text{CO}, J = 1)$ | 13.01$^{+0.08}_{-0.08}$ | 13.63$^{+0.18}_{-0.18}$ | 13.75$^{+0.09}_{-0.09}$ |
| $\log N(\text{CO}, J = 2)$ | 12.91$^{+0.08}_{-0.08}$ | 14.19$^{+0.10}_{-0.09}$ | 13.37$^{+0.10}_{-0.10}$ |
| $\log N(\text{CO}, J = 3)$ | 12.30$^{+0.22}_{-0.54}$ | 13.25$^{+0.11}_{-0.11}$ | 13.36$^{+0.16}_{-0.16}$ |
Noterdaeme et al. (2011) (J0857+1855, J1047+2057, J1705+3543), Balashev et al. (2011) (J1232+0815), Noterdaeme et al. (2010) (J1237+B10647), Srianand et al. (2008) (J1439+1118), Ledoux et al. (2003) (B1444+0126), Ranjan et al. (2018) (J1513+0352), Jorgenson et al. (2010) (J2100−0641, Keck), and Noterdaeme et al. (2015) (J2140−0321). For most DLAs we use the measured populations of H$_2$ and CO rotational levels and C I fine-structure levels. In addition, we determined the parameters of the C I and CO absorption systems in the DLAs towards J0857+1855, J1047+2057, and J1705+3543. The results of our measurements are presented in Table 1. To analyze the absorption systems, we use the standard procedure of comparing the observed and synthetic spectra described in our previous papers (see, e.g., Balashev et al. 2019; Klimenko et al. 2020).

**PHYSICAL CONDITIONS IN THE ISM**

Neutral carbon and molecular hydrogen are known to be tracers of cold gas in the diffuse phase of the ISM (see, e.g., Srianand et al. 2005; Balashev et al. 2019). Observations show that C I was detected only in the absorption systems where molecular hydrogen (H$_2$) is present, i.e., the C II/C I transition occurs in the region where hydrogen is already predominantly in the molecular phase. Physically, this can be caused by the absorption of C I-ionizing photons with energies <13.6 eV (the C I ionization potential is 11.26 eV) by H$_2$ molecules in Lyman and Werner transition lines and an enhanced gas number density in the molecular H$_2$ cloud. Therefore, we think that H$_2$ and C I are spatially linked, while the populations of their energy levels correspond to the same physical conditions in the ISM.

In molecular clouds with a column density log $N$(H$_2$) > 18 the lower H$_2$ J = 0, 1, 2 rotational levels, as a rule, are thermalized ($T_{\text{rot}}$(H$_2$) ≃ $T_{\text{kin}}$), and their populations are determined by the ISM thermal balance, which depends mainly on the UV background intensity and gas number density. However, for simulations of the H$_2$ level populations it is necessary to compute the UV radiation transfer in lines and to solve the thermal and chemical balance equations in a consistent way. For this purpose, we use the grid of molecular cloud models calculated by Klimenko and Balashev (2020) with the application of the PDR Meudon code (Le Petit et al. 2006). An example of an analysis is shown in Fig. 1. The excitation of C I fine-structure levels turns out to have an almost orthogonal dependence on the ISM parameters (UV background intensity and gas number density) compared to the dependence for the lower H$_2$ rotational levels. A joint analysis of the H$_2$ and C I populations breaks the degeneracy in parameters, which allows the gas number density and the UV background in a molecular cloud to be determined with high reliability. To estimate the kinetic temperature, we use the H$_2$ excitation temperature calculated for the first three rotational levels. An analysis of the PDR Meudon models shows good agreement between these parameters in the part of the molecular cloud shielded from UV radiation.

In studying the physical conditions through numerical simulations (Klimenko and Balashev 2020), it is difficult to carefully take into account the dependence of the C I level populations on CMB temperature, and we used some mean CMB temperature for the sample being investigated. Since the excitation by the CMB radiation in a dense interstellar medium ($n_H$ ∼ 100 cm$^{-3}$) is not the main C I level excitation mechanism (see, e.g., Silva and Viegas 2002), this approximation gives a good estimate of the physical conditions. By assuming that the CO molecules are located in the same region as are the C I atoms, we can use the gas number density and temperature from Klimenko and Balashev (2020) as a priori distributions to estimate the collisional pumping rate of molecular CO rotational levels.

The populations of C I fine-structure levels are dependent both on the gas number density and UV background intensity and on the CMB temperature. Therefore, to determine $T_{\text{CMB}}$, we performed an independent calculation of the level populations by taking into account the variations of all three parameters.

**THE POPULATIONS OF ATOMIC C I FINE-STRUCTURE LEVELS**

The model describing the excitation of C I levels has five free parameters: the gas number density, the kinetic temperature, the UV radiation intensity, the CMB temperature, and the C I (J = 0) ground level population. We use the model of a homogeneous cloud in which C I atoms collide with H, H$_2$, and He and are irradiated by direct UV and isotropic CMB radiations. The collisional rate coefficients for C I were taken from Schroder et al. (1991), Staemmler and Flower (1991), and Abrahamsson et al. (2005). We also neglect the self-shielding of UV radiation in C I lines, which are usually optically thin. An analysis of the H$_2$ rotational level populations gives an independent constraint on the kinetic temperature, the gas number density, and the UV radiation intensity (Fig. 1). Therefore, we use the constraints obtained from the analysis of H$_2$ level populations in Klimenko and Balashev (2020) as a priori distributions for the gas number density, the kinetic temperature, and the UV radiation intensity. The parameters and their statistical uncertainties were determined by the Markov
chain Monte Carlo method. The results of our analysis of the C I systems are presented in Table 2. For nine systems the CMB temperature is determined with an uncertainty $\sim 2$–4 K, in three systems only upper limits can be set. In the J1439+1118 and B1444+0126 absorption systems the measured C I level populations are not described by our model and, therefore, they are not used to estimate the redshift dependence of $T_{\text{CMB}}$ below.

In addition, we checked that an analysis of the H$_2$ and C I level populations in absorption systems in our Galaxy gives an estimate of the CMB temperature $T^0_{\text{CMB}} = 1$–4 K with an uncertainty of 2–3 K. The agreement with the estimate of $T^0_{\text{CMB}} = 2.7255$ K (Fixsen 2009) and the small statistical uncertainty confirm the reliability of our method.

THE POPULATIONS OF MOLECULAR CO ROTATIONAL LEVELS

In absorption systems with a high redshift $z \sim 2$ the direct excitation rate of CO rotational levels by CMB photons is much higher than the collisional pumping rate. Therefore, the excitation temperature of lower rotational levels $T_{\text{exc}}$(CO) is close to the CMB temperature $T_{\text{CMB}}$ (Srianand et al. 2008) and can be used to estimate $T_{\text{CMB}}(z)$ (Noterdaeme et al. 2011). However, we showed that the applying a correction for the collisional pumping could lead to a slight, but systematic increase in $T_{\text{exc}}$(CO) compared to $T_{\text{CMB}}(z)$ (Sobolev et al. 2015), which is important to take into account when measuring the deviation of the CMB temperature from the standard relation ($T^0_{\text{CMB}} \times (1 + z)$).

We use the Markov chain Monte Carlo method, in which the estimates of $n_{\text{H I}}$ and $T_{\text{kin}}$ from Klimenko...
Table 2. A list of the high-redshift H$_2$/C I absorption systems in the spectra of quasars for which the physical conditions were analyzed and the CMB temperature was measured

| QSO            | $z_{\text{abs}}$ | $T_{02}(H_2)$, K | $\log n_H$ [cm$^{-3}$] | $\log I_{\text{UV}}$, Mathis field | $T_{\text{CMB}}$(C I), K |
|----------------|------------------|------------------|--------------------------|-----------------------------------|--------------------------|
| J0000+0048     | 2.5255           | 97$^{+4}_{-4}$   | 1.49$^{+0.25}_{-0.70}$ | $<1$                              | 11.1$^{+1.5}_{-6.6}$    |
| B0528−2505     | 2.8111           | 166$^{+8}_{-8}$  | 2.49$^{+0.07}_{-0.11}$ | 1.15$^{+0.15}_{-0.15}$            | $<20$                    |
| J0812+3208     | 2.6264           | 52$^{+3}_{-3}$   | 2.55$^{+0.16}_{-0.18}$ | 0.04$^{+0.21}_{-0.23}$            | $<20$                    |
| J0816+1446     | 3.2874           | 80$^{+6}_{-5}$   | 1.77$^{+0.45}_{-0.80}$ | $-0.13^{+0.26}_{-0.30}$           | 10.8$^{+1.4}_{-3.3}$    |
| J0843+0221     | 2.7866           | 123$^{+8}_{-8}$  | 1.94$^{+0.12}_{-0.10}$ | 1.83$^{+0.12}_{-0.13}$            | $<16$                    |
| J1232+0815     | 2.3377           | 64$^{+4}_{-4}$   | 2.03$^{+0.17}_{-0.18}$ | $-0.13^{+0.40}_{-0.37}$           | $<9.4$                   |
| J1237+0647     | 2.6896           | 178$^{+102}_{-50}$ | 1.19$^{+0.18}_{-0.17}$ | 0.87$^{+0.18}_{-0.15}$            | $<13.8$                  |
| J1439+1118     | 2.4184           | 117$^{+15}_{-17}$ | 0.98$^{+0.20}_{-0.25}$ | 0.68$^{+0.20}_{-0.24}$            | $<13.7$                  |
| B1444+0126     | 2.0870           | 172$^{+32}_{-23}$ | 2.16$^{+0.27}_{-0.26}$ | 0.59$^{+0.25}_{-0.25}$            | $<10.5$                  |
| J1513+0352     | 2.4636           | 89$^{+4}_{-4}$   | 1.95$^{+0.16}_{-0.36}$ | 0.40$^{+0.40}_{-0.69}$            | 8.0$^{+4.0}_{-4.0}$     |
| J2100−0641     | 3.0915           | 84$^{+3}_{-3}$   | 2.02$^{+0.15}_{-0.03}$ | $<-0.10$                          | 12.9$^{+3.3}_{-4.5}$    |
| J2140−0321     | 2.3399           | 83$^{+5}_{-4}$   | 2.93$^{+0.23}_{-0.18}$ | 1.54$^{+0.20}_{-0.21}$            | $<20$                    |

From left to right, the columns give the quasar coordinates, absorption system redshifts, H$_2$ excitation temperatures, gas number densities, UV interstellar background intensities, and CMB temperatures determined by analyzing the C I fine-structure level populations.

Table 3. A list of high-redshift CO absorption systems

| Name           | $z$ | $T_{\text{exc}}$(CO), K | $T_{\text{CMB}}$(z), K | $\log n_H$ [cm$^{-3}$] | $T_{02}(H_2)$, K | $T_{\text{CMB}}$(CO), K |
|----------------|-----|--------------------------|------------------------|--------------------------|------------------|------------------------|
| J0000+0048     | 2.5244 | 9.85$^{+0.71}_{-0.56}$   | 9.6                    | 1.31$^{+0.24}_{-0.42}$  | 97$^{+4}_{-4}$  | 9.81$^{+0.67}_{-0.61}$  |
| J0857+1855     | 1.7294 | 8.9$^{+1.5}_{-1.2}$     | 7.4                    | 2.31$^{+0.70}_{-0.20}$  | 100              | 7.9$^{+1.7}_{-1.4}$    |
| J1047+2057     | 1.7738 | 6.87$^{+0.70}_{-0.70}$  | 7.5                    | $<2.5$                   | 100              | 6.6$^{+1.2}_{-1.1}$    |
| J1237+0647     | 2.6896 | 10.5$^{+0.81}_{-0.62}$  | 10.1                   | 1.27$^{+0.14}_{-0.10}$  | 178$^{+102}_{-57}$ | 10.35$^{+0.78}_{-0.65}$ |
| J1439+1118     | 2.4184 | 9.09$^{+0.85}_{-0.69}$  | 9.3                    | 0.96$^{+0.15}_{-0.18}$  | 107$^{+33}_{-20}$ | 9.04$^{+0.86}_{-0.70}$  |
| J1705+3543     | 2.0377 | 9.1$^{+1.8}_{-1.4}$    | 8.3                    | 2.21$^{+0.17}_{-0.68}$  | 100              | 8.6$^{+1.9}_{-1.4}$    |

From left to right, the columns give the absorption system redshifts, CO excitation temperatures, CMB temperatures, gas number densities, the H$_2$ excitation temperatures, and CMB temperatures estimated by analyzing the molecular CO rotational level populations.
and Balashev (2020) are taken into account as a priori distributions. Our model has four free parameters: the gas number density, the kinetic temperature, the CMB temperature, and the CO ($J = 0$) ground level population. The model assumes a uniform distribution of molecules over the cloud and takes into account two CO rotational level excitation mechanisms: collisions with H, H$_2$, and He and direct excitation by CMB photons. The CO collisional rate coefficients were taken from Walker et al. (2015), Yang et al. (2016), and Cecchi-Pestellini et al. (2002). We measured $T_{\text{CMB}}(z)$ in six known high-redshift CO absorption systems. The results are presented in Table 3.

In the J0857+1855, J1047+2057, and J1705+3543 systems the redshift $z \leq 2$. Therefore, the H$_2$ absorption lines do not fall into the wavelength range of the VLT/UVES spectrographs. To estimate the physical conditions in these systems, we analyzed the CI level populations. The kinetic temperature was assumed to be equal to the typical temperature in a cold diffuse medium (100 K). Our estimates of the gas number density $n_H$ are given in Table 3. In Fig. 2 we compare the CO excitation temperature and the CMB temperature estimated by applying corrections for collisional excitation. The difference between $T_{\text{CMB}}(\text{CO})$ and $T_{\text{exc}}(\text{CO})$ turns out to be significant and is $\sim 10\%$ for J0857+1855 and J1705+3543. Given the correction, the new values of $T_{\text{CMB}}(\text{CO})$ show better agreement with the prediction of the standard model.

**RESULTS**

The CMB temperature measurements in high-redshift CI and CO absorption systems are given

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**Fig. 2.** Comparison of the CO excitation temperature ($T_{\text{exc}}(\text{CO})$, blue squares) and our CMB temperature estimate ($T_{\text{CMB}}(\text{CO})$, red circles) made by analyzing the CO rotational level populations with a correction for the collisional excitation. The black solid line indicates the linear relation according to the standard cosmological ΛCDM model. The blue and red dashed lines indicate the dependences $T_{\text{CMB}}(z) = T_0(1+z)^{1-\beta}$ for alternative cosmological models obtained by analyzing the measurements of $T_{\text{exc}}(\text{CO})$, $\beta = -0.019 \pm 0.028$ (blue curve) and $T_{\text{CMB}}(\text{CO})$, $\beta = -0.007 \pm 0.030$ (red curve).
in Table 4. Figure 3 shows these measurements as a function of redshift, along with other estimates obtained by analyzing the Sunyaev–Zeldovich effect for galaxy clusters (Battistelli et al. 2002; Luzzi et al. 2009; Hurier et al. 2014) and analyzing the absorption lines of molecules in a lensing galaxy at $z = 0.89$ in the spectrum of the quasar PKS 1830-211 (Müller et al. 2013).

The direct measurements of $T_{\text{CMB}}(z)$ in the CO and CI absorption systems agree well with the prediction of the standard cosmological model. The estimates based on the analysis of the CI fine-structure level populations have a greater statistical uncertainty than do the estimates based on the analysis of the CO rotational level populations. This is because the dependence of the CI level populations on CMB temperature is weaker.

Using the expression $T_{\text{CMB}}(z) = T_0(1 + z)^{1-\beta}$ (with $T_0 = 2.7255 \pm 0.0006$, Fixsen 2009), we determine the parameter $\beta$ for different data samples. The results are presented in Table 5. The measurements using CI and CO at high redshifts are consistent with the standard relation ($\beta = 0$) within the uncertainties, $\beta = -0.015_{-0.028}^{+0.030}$. The measurements of $T_{\text{CMB}}(z)$ using galaxy clusters give a positive value of $\beta = 0.013 \pm 0.017$. Our estimate for both samples gives a constraint $\beta = 0.010 \pm 0.013$. Our estimate is slightly higher than the estimate, $\beta = 0.006 \pm 0.013$, from Hurier et al. (2014) due to a difference in the CO data. The systematic effect related to the inclusion of collisional CO excitation has a magnitude comparable to the statistical uncertainty in the $\beta$ estimate: $\beta = -0.007_{-0.031}^{+0.030}$ versus $-0.019_{-0.029}^{+0.028}$ for the CO data with and without the correction. This leads to an effective increase in the new $\beta$ estimate compared to the estimate by Hurier et al. (2014).

**An Independent Estimate of $T_{\text{CMB}}$ for $z = 0$**

By extrapolating the dependence $T(z)$ to zero redshift ($z = 0$), i.e., by considering $T_0$ as a free parameter when fitting the data with the standard relation $T(z) = T_0(1 + z)$, we obtained an independent estimate of the CMB temperature at the present epoch: $T_0 = 2.719 \pm 0.009$ K. It agrees well with the currently most accurate estimate obtained from satellite observations, $T_0 = 2.7255 \pm 0.0006$ K (Fixsen 2009). The results are presented in Table 6.
Table 4. Measurements of the CMB temperature $T_{\text{CMB}}$ in high-redshift C I and CO absorption systems

| QSO         | $z_{\text{abs}}$ | $T_{\text{CMB}}$(C I), K | $T_{\text{CMB}}$(CO), K |
|-------------|------------------|---------------------------|--------------------------|
| J0857+1855  | 1.7293           | $9.8^{+0.7}_{-0.6}$      |                          |
| J1047+2057  | 1.7738           | $6.6^{+1.2}_{-1.1}$      |                          |
| J1705+3543  | 2.0377           | $8.6^{+1.9}_{-1.4}$      |                          |
| J1232+0815  | 2.3377           | $<9.4$                    |                          |
| J2140−0321  | 2.3399           | $<20$                     |                          |
| J1439+1117  | 2.4184           | $<13.7$                   | $9.04^{+0.9}_{-0.7}$    |
| J1513+0352  | 2.4636           | $8.0^{+1.0}_{-1.0}$      |                          |
| J0000+0048  | 2.5255           | $11.1^{+1.5}_{-6.6}$     | $9.8^{+0.7}_{-0.6}$    |
| J0812+3208  | 2.6264           | $<20$                     |                          |
| J1237+0647  | 2.6896           | $<13.8$                   | $10.4^{+0.7}_{-0.7}$    |
| J0843+0221  | 2.7866           | $<16$                     |                          |
| B0528−2505  | 2.8111           | $<20$                     |                          |
| J2100−0641  | 3.0915           | $12.9^{+3.3}_{-4.5}$     |                          |
| J0816+1446  | 3.2874           | $15.3^{+1.0}_{-4.2}$     |                          |

Table 5. Constraints on the parameter $\beta$ characterizing the deviation of the CMB temperature from the standard relation of evolution of the temperature $T_{\text{CMB}} = (2.7255 \pm 0.0006) \times (1 + z)^{1-\beta}$

| Data         | $\beta$          | Reference     |
|--------------|------------------|---------------|
| CO           | $-0.007^{+0.030}_{-0.031}$ | [a]           |
| C I          | $-0.077^{+0.130}_{-0.075}$ | [a]           |
| C I + CO     | $-0.015^{+0.030}_{-0.028}$ | [a]           |
| SZ           | $0.13^{+0.017}_{-0.017}$ | [b, c, d]     |
| Mol          | $0.023^{+0.031}_{-0.032}$ | [e]           |
| Mol + SZ + C I | $0.014^{+0.014}_{-0.015}$ | [a, b, c, d, e] |
| Mol + SZ + CO | $0.011^{+0.014}_{-0.013}$ | [a, b, c, d, e] |
| Mol + SZ + C I + CO | $0.010^{+0.013}_{-0.013}$ | [a, b, c, d, e] |

[a]—this paper, [b]—Battistelli et al. (2002), [c]—Luzzi et al. (2009), [d]—Hurier et al. (2014), [e]—Müller et al. (2013).

A Constraint on the Equation of State for Dark Energy

Within the framework of an alternative cosmological model, the deviation of the redshift dependence of the CMB temperature from the linear relation can be caused by the formation and destruction of photons during the decay of dark energy (see, e.g., Lima et al. 2011). Jetzer et al. (2011) applied this phenomenological model to describe the CMB temperature measurements and estimated the parameter of the effective equation of state for dark energy $p = w_{\text{eff}} \rho$, $w_{\text{eff}} = -0.97 \pm 0.03$. Using Eq. (22) from Jetzer et al. (2011) and new CMB temperature measurements in galaxy clusters and absorption systems, we obtained the constraint $w_{\text{eff}} = -0.991^{+0.014}_{-0.012}$. We additionally used the assumption that the adiabatic index is equal to its canonical value of $\gamma = 4/3$ and the constraints on the parameters $T_0 = 2.72548 \pm 0.00057$ (Fixsen 2009) and $\Omega_{m0} = 0.315 \pm 0.007$ (Planck Collaboration 2020). Our estimate is consistent with other estimates, $w_{\text{eff}} = -0.996 \pm 0.025$ (Noterdaeme et al. 2011) and 0.995 $\pm$ 0.011 (Hurier et al. 2014).

CONCLUSIONS

We presented the CMB temperature measurements in high-redshift CO and C I absorption systems in quasar spectra. In comparison with the previous measurements, we took into account the collisional excitation of CO rotational levels. We showed that the CO excitation temperature systematically exceeds the CMB temperature, for some systems the difference reaches 1 K. Applying corrections for collisional excitation gives better agreement of the CMB temperature measurements with the standard cosmological model (deviation parameter $\beta = -0.004^{+0.049}_{-0.059}$). For atomic C I systems we measured the CMB temperature by taking into account the collisional excitation and radiative pumping. We showed that a consistent analysis of the populations of C I fine-structure levels and H$_2$ rotational levels well determines the physical conditions in the ISM: the gas number density, the kinetic temperature and intensity of the interstellar radiation field. This allows the contributions from the collisional and radiative pumping of C I fine-structure levels to be carefully taken into account. The statistical uncertainty of the $T_{\text{CMB}}(z)$ estimate by this method is a factor of 2–3 higher than that for the estimates based on the analysis of the excitation of CO rotational levels. At the same time, the number of known C I absorption systems at high redshifts is considerably higher than the number of known CO systems.
Table 6. Results of the local CMB temperature measurements at $z = 0$ using COBE/FIRAS data (Fixsen 1996, 2009) and an independent estimate of $T_{\text{CMB}}(z)$ from the measurements of $T_{\text{CMB}}(z)$ in galaxy clusters and absorption systems in the spectra of quasars assuming the standard model of evolution of $T_{\text{CMB}}(z)$

| Data                      | $T_{\text{CMB}}(z = 0)$, K | $\beta$ |
|---------------------------|-----------------------------|---------|
| Fixsen (1996)             | 2.728 ± 0.004               |         |
| Fixsen (2009)             | 2.7255 ± 0.0006             |         |
| Mol + SZ + CI + CO        | 2.719 ± 0.009               | 0       |
| Mol + SZ + CI + CO + Fixsen (2009) | 2.7255 ± 0.0006             | 0.010 ± 0.013 |

The lower row gives the final estimates of the parameters for the standard linear model of $T_{\text{CMB}}(z)$ by taking into account all of the CMB temperature measurements.

Combining our measurements of $T_{\text{CMB}}(z)$ in absorption systems with the constraints from galaxy clusters, we obtained a constraint on the parameter $\beta = +0.010 \pm 0.013$. This estimate provides a stringent constraint on the parameter of the effective equation of state for decaying dark matter ($\omega_{\text{eff}} = -0.991^{+0.014}_{-0.012}$). The CMB temperature at the present epoch was independently estimated by assuming the standard relation $T(z) = T_0 (1+z)$: $T_0 = 2.719 \pm 0.009$ K.

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