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The cosmic microwave background radiation temperature at $z_{\rm abs} = 3.025$ toward QSO 0347–3819*

P. Molaro[1], S. A. Levshakov[2,**], M. Dessauges-Zavadsky[3,4], and S. D'Odorico[3]

[1] Osservatorio Astronomico di Trieste, via G.B. Tiepolo 11, 34131 Trieste, Italy
[2] Division of Theoretical Astrophysics, National Astronomical Observatory, Mitaka, Tokyo 181-8588, Japan
[3] European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching bei München, Germany
[4] Observatoire de Genève, 1290 Sauverny, Switzerland

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Abstract. From the analysis of the C^+ fine-structure population ratio in the damped Lyα system at $z_{\rm abs} = 3.025$ toward the quasar Q0347–3819 we derive an upper bound of 14.6 ± 0.2 K on the cosmic microwave background temperature ($T_{\rm CMBR}$) regardless the presence of other different excitation mechanisms. The analysis of the ground state rotational level populations of H_2 detected in the system reveals a Galactic-type UV radiation field ruling out UV pumping as an important excitation mechanism for C^+. The low dust content estimated from the Cr/Zn ratio indicates that the IR dust emission can also be neglected. When the collisional excitation is considered, we measure a temperature for the cosmic background radiation of $T_{\rm CMBR} = 12.1^{+1.7}_{-3.2}$ K. The results are in agreement with the $T_{\rm CMBR} = 10.968 \pm 0.004$ K predicted by the hot Big Bang cosmology at $z_{\rm abs} = 3.025$.

Key words. cosmology: observations: cosmic microwave background – quasars: absorption lines: individual: Q0347–3819

1. Introduction

In the standard Big Bang model (SBB) the temperature of the relic radiation from the hot phase of the Universe is predicted to increase linearly with redshift: $T_{\rm CMBR}(z) = T_{\rm CMBR}(0)\,(1+z)$ (e.g., Peebles 1993). At the present epoch direct measurements show that $T_{\rm CMBR}(0) = 2.725 \pm 0.001$ K (1σ c.l.), and that the relic radiation follows a Planck spectrum with very high precision (Mather et al. 1999).

As pointed out by Bachall & Wolf (1968) the CMBR temperatures at earlier epochs can be measured from the analysis of quasar absorption line spectra which show atomic and/or ionic fine-structure levels excited by the photo-absorption of the CMBR. Among the species with fine structure levels the C I and C II show an energy separation, from 23.6 K up to 91.3 K, which make them sensitive to the CMBR, in particular as the redshift increases. However, C I is generally fully ionized and rarely detected, while the C II ground-state transitions are strongly saturated, thus making column densities rather uncertain. In addition, non cosmological sources (such as particle collisions, pumping by UV radiation, IR dust emission and by other sources) may compete with the CMBR to populate the excited fine-structure levels. Only independent knowledge of ambient radiation field and of particle densities allows to disentangle the contribution of the background radiation from that of other mechanisms. For these reasons previous measurements place upper limits to $T_{\rm CMBR}$ rather than real measurements, albeit quite stringent ones (Meyer et al. 1986; Songaila et al. 1994; Lu et al. 1996; Ge et al. 1997; Roth & Bauer 1999; Ge et al. 2001).

Recently, Srianand et al. (2000) from the H_2 analysis in the DLA at $z_{\rm abs} = 2.3371$ toward the quasar Q1232+0815 were able to infer the UV radiation field in the absorber. Then by means of C I, C I*, C I**, C II and C II* they obtained a $T_{\rm CMBR} = 10 \pm 4$ K, while SBB predicts $T_{\rm CMBR} = 9.09$ K. However, the H_2 abundance measurement at $z_{\rm abs} = 2.3371$ by Srianand et al. (2000) is in contradiction with their recent estimation of the deuterated molecular hydrogen abundance (Varshalovich et al. 2001). The ratio $HD/H_2 \simeq (0.8 \div 3.0) \times 10^{-3}$, whereas it is $10^{-7} \div 10^{-6}$ in the ISM diffuse clouds (e.g. Wright & Morton 1979). Until this discrepancy is clarified the value of Srianand et al. (2000) should be taken as an upper limit of $T_{\rm CMBR} < 14$ K at $z_{\rm abs} = 2.3371$. So far all measurements have been found to be consistent with the SBB model prediction.

Send offprint requests to: P. Molaro,
e-mail: `molaro@oat.ts.astro.it`

* Based on public data released from UVES Commissioning at the VLT Kueyen telescope, ESO, Paranal, Chile.

** On leave from the Ioffe Physico-Technical Institute, Russian Academy of Sciences, St. Petersburg.

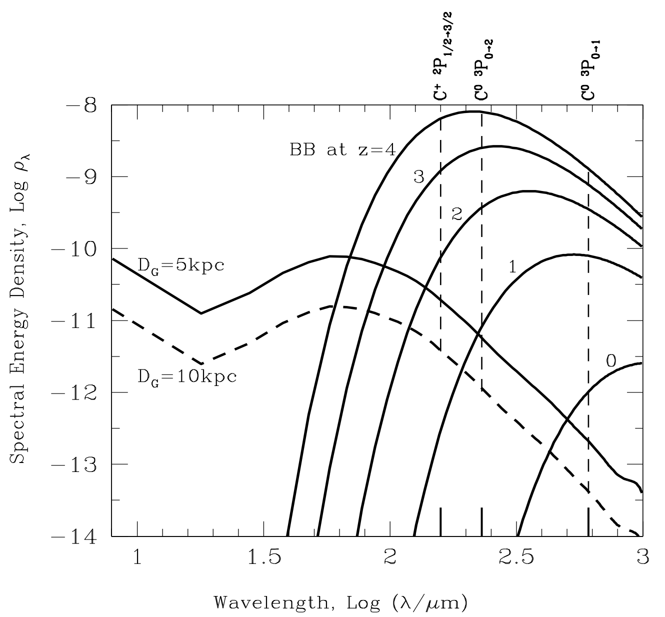

Fig. 1. The Galactic interstellar radiation fields at galactocentric distances $D_{\rm G} = 5$ and 10 kpc from Mathis et al. (1983) are compared with the black body spectra calculated at different redshifts using the relation $T_{\rm CMBR}(z) = T_{\rm CMBR}(0)\,(1+z)$. The positions of the excited levels of C^0 and C^+, suitable to constrain the $T_{\rm CMBR}$ values at different redshifts, are indicated by vertical dashed lines.

In this letter, we present a new measurement of $T_{\rm CMBR}$ at higher redshift, $z_{\rm abs} = 3.025$, from the VLT/UVES spectra of Q0347–3819.

2. Data analysis and results

The spectroscopic observations of Q0347–3819 obtained during UVES commissioning at the VLT 8.2 m telescope are described in detail by D'Odorico et al. (2001) and by Levshakov et al. 2002 (LDDM, hereinafter).

In LDDM relevant physical properties for the damped Lyα system (DLA) at $z_{\rm abs} = 3.025$ are obtained by analyzing numerous H_2 and metal absorption lines associated to the DLA. The $z_{\rm abs} = 3.025$ system exhibits a multicomponent velocity structure spanning over $\sim$80 km s^{-1}. The main component at $z_{\rm abs} = 3.024855$ has a hydrogen column density of $N(\mbox{H\,I}) = 2.52(\pm0.04)\times10^{20}$ cm^{-2} and shows the presence of molecular hydrogen with a fractional abundance of $f(\mathrm{H_2}) = 3.25(\pm0.17)\times10^{-6}$. Several neutral and ionized species associated with this cloud have been analyzed. In particular the C II 1036.3367 and C II* 1037.0182 lines have been identified.

A line absorption model for the $z_{\rm abs} = 3.025$ system which is able to reproduce the line profiles for the whole set of atomic and ionic species has been elaborated in LDDM. This model allows to get a reliable column density of the saturated lines. LDDM obtained a column density of $N(\mbox{C\,II}) = 5.05(\pm0.28)\times10^{15}$ cm^{-2} for the C II 1036.3 main component. This C column density is consistent with what can be inferred from the other elements measured in the system by means of unsaturated lines. For instance, if C goes in lockstep with the undepleted Zn II we would obtain $N(\mbox{C\,II}) = 3.1\times10^{15}$ cm^{-2}, assuming solar photospheric values from Grevesse & Sauval (1998), while we would obtain $N(\mbox{C\,II}) = 5.8\times10^{15}$ cm^{-2} if C follows Ar I, with the Ar solar value quoted in Sofia & Jenkins (1998). Neutral carbon is not detected and N(C I)/N(C II) $< 7.9\times10^{-5}$.

The column density for the $N(\mbox{C\,II}^*)$ 1037.0182 main component is $2.26(\pm0.12)\times10^{13}$ cm^{-2}. Prochaska & Wolfe (1999) reported the detection of the C II 1334.5323 and C II* 1335.7077 lines in the same system. For the latter line, which is unsaturated, they provide a column density of $N(\mbox{C\,II}^*) = 3.00(\pm0.23)\times10^{13}$ cm^{-2}, which refers to the total system. When we correct this value according to the relative ratios between the components [1 : 0.195 : 0.044 : 1.952 (LDDM)], we obtain for the main one $N(\mbox{C\,II}^*) = 1.83(\pm0.14)\times10^{13}$ cm^{-2}. The C II* 1335.7077 line is likely blended with the C II* 1335.6627 which produces the blue asymmetry present in the Keck spectrum at –10 km s^{-1} (cf. Fig. 5 in Prochaska & Wolfe). The relative strengths of the two blended transitions is $f_{1335.7}/f_{1335.6} = 8.7$. If we correct $N(\mbox{C\,II}^*)$ by the corresponding factor, for optically thin lines we obtain $N(\mbox{C\,II}^*) = 1.64(\pm0.11)\times10^{13}$ cm^{-2} (main component). The weighted mean between the VLT and Keck quantities is $N(\mbox{C\,II}^*) = 1.92(\pm0.08)\times10^{13}$ cm^{-2}. Combining this value with the ground level column density obtained from the VLT we derive a ratio $N(\mbox{C\,II}^*)/N(\mbox{C\,II}) = 3.8(\pm0.3)\times10^{-3}$.

The ground state of the C^+ ion consists of two levels $2s^22p\ ^2P^0_{1/2,3/2}$ with an energy separation of $\Delta E = 63.42$ cm^{-1} which corresponds to $\lambda = 157.7$ μm. The excited level can be populated by several mechanisms such as collisions, fluorescence or IR photon absorption, which include also the CMBR. In the following we use an effective temperature $T_{\rm eff}$ to characterize at $\lambda = 157.7$ μm the proper spectral energy density of the local IR field approximated by a Planck spectrum with $T = T_{\rm eff}$.

In equilibrium, the population ratio of the upper level n_2 to the lower level n_1, in ions with a doublet fine structure in the ground state, is given by:

$$\frac{n_2}{n_1} = \frac{Q_{1,2} + w_{1,2}}{Q_{2,1} + A_{2,1} + w_{2,1}}\ , \qquad (1)$$

where $w_{1,2}$, $w_{2,1}$ and $Q_{1,2}$, $Q_{2,1}$ are the photo-absorption, radiative decay, collisional excitation and de-excitation rates, respectively. $A_{2,1}$ is the radiative transition probability which is $A_{2,1} = 2.291\times10^{-6}$ s^{-1} for C^+.

If only the background radiation contributes to the population of the excited fine-structure states, Eq. (1) gives:

$$T_{\rm CMBR}(z) = \frac{91.325}{\ln\,[g^*\,N(\mbox{C\,II})/g\,N(\mbox{C\,II}^*)]}\ , \qquad (2)$$

where g^* and g are the statistical weights of the corresponding levels. Thus the estimated $N(\mbox{C\,II}^*)/N(\mbox{C\,II})$ ratio would yield $T_{\rm eff} = 14.6\pm0.2$ K, which can be considered as a firm upper limit to the $T_{\rm CMBR}$. The value expected from the standard model at $z_{\rm abs} = 3.025$ is of $T_{\rm CMBR} = 10.968 \pm 0.004$ K. Thus the observed $N({\rm C\,II}^*)/N({\rm C\,II})$ ratio provides a stringent limit to the $T_{\rm CMBR}$ at $z_{\rm abs} = 3.025$ with only little room left for extra contributions.

In the following we show how the detection of H_2 in the same component where C II* and C II are observed can provide additional information on the presence of other excitation processes. In this discussion we assume that the molecular and ionic species trace the same material as it is suggested by the similar broadening shown by the line profiles and by the absence of any evidence for an associated dense H II region gas on the line of sight as argued in LDDM from the non detection of the N II* 1084.580 and 1084.562 lines.

The H_2 populations over the $J = 0$ to $J = 5$ rotational levels of the ground electronic-vibrational state provide an excitation temperature of $T_{\rm ex} = 825 \pm 110$ K and the kinetic temperature is also estimated to be $T_{\rm kin} \lesssim 430$ K (LDDM). The population ratios of the higher J levels $N(5)/N(3)$ and $N(4)/N(2)$ are sensitive to the UV pumping. The measured rate of photo-absorption $\beta_0 \approx 2 \times 10^{-9}$ s^{-1} is very close to the average interstellar radiation field in the Galaxy. With this constraint on the UV flux the fluorescent excitation process has a rate $\simeq 9.3 \times 10^{-11}$ s^{-1}, which is rather low and can be neglected according to Silva & Viegas (2001).

The rates of the radiative processes $w_{1,2}$ and $w_{2,1}$ may be caused by the cosmic microwave background radiation at $z_{\rm abs} = 3.025$, but also by local sources of infrared radiation like diffuse emission from dust heated by OB stars to temperatures $T \simeq 10 \div 20$ K as observed in the Milky Way (Mathis et al. 1983). The possible contribution from the heated dust is illustrated in Fig. 1 where the MW interstellar radiation fields at galactocentric distances $D_{\rm G} = 5$ and 10 kpc are shown along with the black body spectra calculated at different redshifts using the linear relation $T_{\rm CMBR}(z) = T_{\rm CMBR}(0)\,(1+z)$. This is representative of our system since, as we have discussed above, the intensity of the UV field in the $z_{\rm abs} = 3.025$ cloud is found to be of the same order of magnitude as in the MW. The positions of the excited levels of C^0 and C^+, which are suitable to restrict $T_{\rm CMBR}$, are also indicated by vertical lines. Figure 1 shows that the diffuse FIR reemission of stellar radiation by dust grains, if the dust emissivity at $\lambda = 157.7$ μm is equal to the highest value measured at $D_{\rm G} = 5$ kpc in the MW, always remains lower than the expected CMBR. The corresponding photo-absorption rate is $w_{1,2}^{\rm dust} \simeq 1.8 \times 10^{-11}$ s^{-1}, but the expected rate induced by the relic radiation is $w_{1,2}^{\rm CMBR} \simeq 1.1 \times 10^{-9}$ s^{-1}. Moreover, LDDM estimated from the [Cr/Zn] abundance ratio that the dust content in the $z_{\rm abs} = 3.025$ absorbing region is about 30 times lower as compared with the MW mean value, so that we may exclude significant contribution from dust emission.

We now consider the information on the particle density, since the upper level of C^+ may be populated by collisions with several particles such as electrons, e^-, hydrogen atoms, H^0, protons, H^+, and molecules, H_2. The $J = 2$ level of H_2 has a rather long radiative lifetime and is the more sensitive to the collisional de-excitation. The critical density above which collisional de-excitation becomes important is $n_{\rm H}^{\rm cr} = 3.6$ cm^{-3} (LDDM) and, therefore, $n_{\rm H} \geq 4$ cm^{-3} is required to maintain the observed $N(2)/N(0)$ ratio at $T_{\rm kin} \simeq 400$ K. Arguments based on the production rate of H_2 imply that the volumetric gas density, $n_{\rm H}$, ranges between 4 and 14 cm^{-3}.

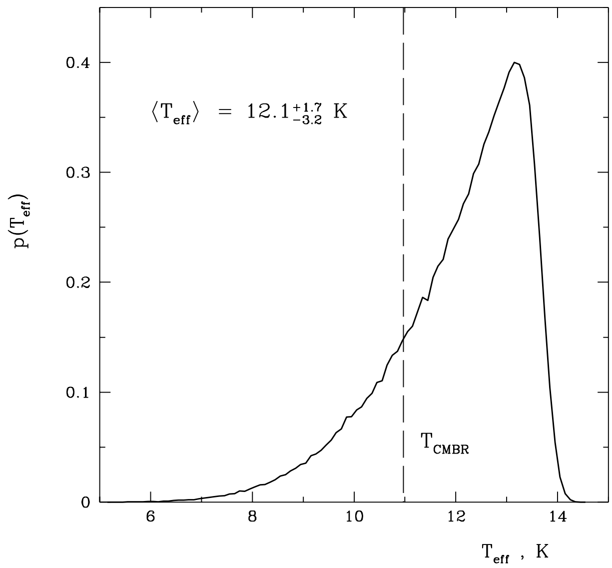

Fig. 2. Monte Carlo simulations of the probability density function of $T_{\rm eff}$ for the value of $N({\rm C\,II}^*)/N({\rm C\,II}) = 3.8 \times 10^{-3}$. The mean value is $T_{\rm eff} = 12.1^{+1.7}_{-3.2}$ K [the $\frac{1}{2}(1-p)$ and $\frac{1}{2}(1+p)$ quantiles were used to estimate the uncertainty interval at $p = 0.95$]. The $T_{\rm CMBR}$ from the standard Big Bang cosmological model is marked with a vertical dashed line.

The H^0–C^+ collisional rate is of $Q_{1,2}^{\rm H^0} \simeq 1.45 \times 10^{-9}\,n_{\rm H}$ s^{-1} in the range 10^2 K $< T_{\rm kin} < 10^3$ K (Launay & Roueff 1977). Collisions with electrons have the highest rates but the electron density is rather low. Electrons in H I regions come mainly from carbon photo-ionization, so that $n_{\rm e} \simeq ({\rm C/H})\,n_{\rm H}$, which is $\simeq 3 \times 10^{-5}\,n_{\rm H}$ for the $z_{\rm abs} = 3.025$ system. The rate is $Q_{1,2}^{\rm e^-} \simeq 2 \times 10^{-7}\,n_{\rm e}$ s^{-1} and therefore the collisional rate becomes $Q_{1,2}^{\rm e^-} \simeq 6 \times 10^{-12}\,n_{\rm H}$ s^{-1}, which is much lower than that of the hydrogen collisions for the same temperature interval (Silva & Viegas 2001). H_2 molecules do not contribute to collisions considering the low fractional abundance measured in the system. The corresponding de-excitation rate, calculated from the principle of detailed balance, is $Q_{2,1}^{\rm H^0} \simeq 9.11 \times 10^{-10}\,n_{\rm H}$ s^{-1}, for $T_{\rm kin} \simeq 400$ K.

We calculated the probability density function of $T_{\rm eff}$ using statistical Monte Carlo simulations which suggest that the errors are normally distributed around the mean value of $N({\rm C\,II}^*)/N({\rm C\,II})$ with the dispersion equal to the probable error of this ratio, while $n_{\rm H}$ is evenly distributed between 4 cm^{-3} and 14 cm^{-3}. The result is presented in Fig. 2. The most probable value of $T_{\rm eff}$ obtained

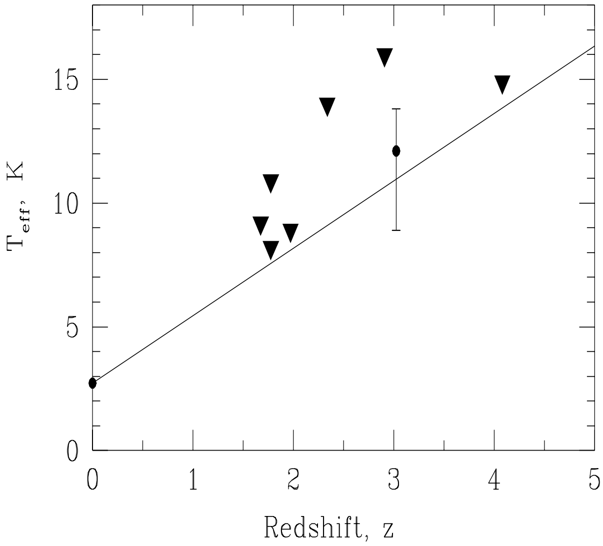

Fig. 3. Measurements of $T_{\rm eff}$ at different redshifts. Upper limits from previous works (Songaila et al. 1994; Lu et al. 1996; Ge et al. 1997; Roth & Bauer 1999; Srianand et al. 2000) are marked by triangles. The dot with error bars shows the estimation of $T_{\rm eff}$ at $z_{\rm abs} = 3.025$ toward Q0347–3819 (this letter). The straight line shows the prediction from the hot Big Bang cosmological model, $T_{\rm CMBR}(z) = T_{\rm CMBR}(0)\,(1+z)$.

in this analysis is $T_{\rm eff} = 12.1^{+1.7}_{-3.2}$ K. The lower and upper errors of $T_{\rm eff}$ correspond to the $\frac{1}{2}(1-p)$ and $\frac{1}{2}(1+p)$ quantiles, respectively (the central 100p% confidence interval was used with $p = 0.95$).

Since we have considered collisions and excluded fluorescence and dust emission as significant processes in the population of the excited levels, $T_{\rm eff}$ is actually $T_{\rm CMBR}$ for this particular DLA. Thus our measurement of $N({\rm C\,II}^*)/N({\rm C\,II}) = 3.8(\pm 0.3) \times 10^{-3}$ leads to the most probable value of $T_{\rm eff} = 12.1$ K which is only 1.1 K higher with respect to the predicted $T_{\rm CMBR}$ and fully consistent within errors.

In Fig. 3 all the previous estimations of $T_{\rm CMBR}$ are shown. Our result, together with upper limits presented in Fig. 3 support the linear evolution of the CMBR within the framework of the SBB model.

Alternative non-adiabatic cosmological models in which photon creation takes place as the Universe expands predict a different temperature-redshift relation of the type $T_{\rm CMBR}(z) = T_{\rm CMBR}(0)\,(1+z)^{(1-\beta)}$ (Lima et al. 2000). At high redshift the deviation becomes more pronounced and our measurement set a limit to $\beta \leq 0.22$ ($2\,\sigma$).

3. Conclusions

The analysis of the H_2 lines in the damped Lyα absorber at $z_{\rm abs} = 3.025$ toward QSO 0347–3819 allows us to estimate the local excitation mechanisms which populate the fine-structure levels together with the $T_{\rm CMBR}$. From the $N({\rm C\,II}^*)/N({\rm C\,II})$ ratio we measure the temperature of the local background radiation of $T_{\rm CMBR} = 12.1^{+1.7}_{-3.2}$ K which is consistent with the temperature of the cosmic background microwave radiation of 10.968 K predicted by the standard Big Bang cosmology at the redshift of the absorber.

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