H$_2$, D/H and the CMBR Temperature at $z = 3.025$ Toward QSO 0347–3819

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Abstract

A new molecular hydrogen cloud has been identified at $z = 3.025$ in the absorption-line spectrum of the quasar 0347–3819 observed with the UVES spectrograph at the VLT/Kueyen telescope. At the same redshift numerous metal lines and the D$\text{I}$ Ly-5, Ly-8, Ly-10, and Ly-12 lines were detected. The simultaneous analysis of metal and hydrogen lines yielded $D/H = (3.75 \pm 0.25) \times 10^{-5}$. This value is consistent with SBBN if the baryon-to-photon ratio, $\eta$, lies within the range $4.4 \times 10^{-10} \leq \eta \leq 5.3 \times 10^{-10}$, implying $\Omega_b h^2_{100} = 0.018 \pm 0.002$ (1 $\sigma$ c.l.). The population of the ground state rotational levels of H$_2$ from $J = 0$ to 5 revealed a Galactic-type UV radiation field in the H$_2$-bearing cloud ruling out UV pumping as an important mechanism for C$^+$. Accounting for two other important excitation mechanisms such as collisions and FIR photon absorption, we were able to measure for the first time the temperature of the cosmic background radiation at $z > 3$, $T_{\text{CMBR}} = 12.1^{+1.7}_{-3.2}$ K, from the analysis of the C$^+$ fine-structure lines. This result supports the value of $T_{\text{CMBR}} = 10.968 \pm 0.004$ K predicted at $z = 3.025$ by the hot Big Bang cosmology.

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 $z$: $T_{\text{CMBR}}(z) = T_{\text{CMBR}}(0)(1 + z)$. At the present epoch direct measure-
ments show that $T_{\text{CMBR}}(0) = 2.725 \pm 0.001$ K (1 $\sigma$ c.l.), and that the relic radiation follows a Planck spectrum with very high precision [4]. However, at earlier cosmological epochs $T_{\text{CMBR}}$ cannot be measured directly. It was suggested that this scaling in proportion to $(1 + z)$ can be tested by observing the population of excited fine-structure lines in the QSO absorption spectra [2].

The relative population of the fine-structure levels may not, however, be caused by photo-absorption of the CMBR only. Non-cosmological sources such as particle collisions, pumping by UV radiation or by IR dust emission may compete with the CMBR to populate the excited fine-structure levels. Only independent knowledge of the ambient radiation field, particle densities and the kinetic temperature of the gas allow to disentangle the contribution of the background radiation from that of other mechanisms. For these reasons previous studies set only upper limits to $T_{\text{CMBR}}$ [3], [4], [5], [6], [7], [8].

The physical parameters in question can be accurately estimated if the absorber is a diffuse molecular cloud. Molecules allow to measure the volumetric gas density $n_H$, the kinetic temperature $T_{\text{kin}}$ and the intensity of the UV radiation field through the analysis of their distribution on the low rotational levels. In particular, intervening molecular clouds showing $H_2$ and the fine-structure lines of $C_1$ and $C_{\text{II}}$ provides a unique opportunity to measure the cosmic microwave background radiation temperature in early cosmological epochs and to test the SBB predictions.

Another observational test of the SBB model is the measurement of the hydrogen isotopic ratio at high $z$. The standard (homogeneous) Big Bang nucleosynthesis (SBBN) predicts the same D/H abundance ratio for any direction in the early Universe since “no realistic astrophysical process other than the Big Bang could produce significant D” [9]. Deuterium is created exclusively in BBN and therefore we can expect that the D/H ratio decreases with cosmic time due to conversion of D into $^3$He and heavier elements in stars. It is clear that the precise measurements of the D/H values at high redshift are extremely important to probe whether BBN was homogeneous. The choice of the appropriate BBN model may in turn place constrains on different models of structure formation.

In this contribution we discuss the role of the $H_2$-bearing cloud with respect to the measurement of D/H and $T_{\text{CMBR}}$ at $z_{\text{abs}} = 3.025$ toward the quasar 0347–3819.

2. Observations and results

The spectroscopic observations of Q0347–3819 ($z_{\text{em}} = 3.23$, $V = 17.3$) obtained with the VLT 8.2 m telescope are described in [10] and [11]. The spectrum
was obtained with the resolutions FWHM $\approx 7.0$ km s$^{-1}$ and $\approx 5.7$ km s$^{-1}$ in the UV and near-IR ranges, respectively. A signal-to-noise ratio of $S/N \approx 10 - 40$ per resolution element was achieved in these observations.

The analysis of the H$_2$, deuterium and metal absorption-lines was performed in \[1\]. We found that the fractional abundance of H$_2$ is $f_{H_2} = (3.3 \pm 0.2) \times 10^{-6}$. This value is similar to that observed in the Galactic diffuse clouds with low color excesses, $E(B-V) < 0.1$. The kinetic gas temperature is found to be less than 430 K. The population of the low rotational levels is represented by a single excitation temperature of $T_{\text{ex}} = 825 \pm 110$ K. The observed population ratios of H$_2$ in different rotational states and the C$^+$/C II ratio give the number density $n_H \approx 6 \text{ cm}^{-3}$, and the cloud dimension along the line of sight $D \approx 14$ pc.

The relative populations of H$_2$ in the $J = 4$ and 5 rotational levels correspond to the rate of photo-destruction $I \approx 2 \times 10^{-10}$ s$^{-1}$. The photo-absorption rate, $\beta_0 \approx I/0.11$, is thus equal to $\beta_0 \approx 2 \times 10^{-9}$ s$^{-1}$. Taking into account that the Galactic interstellar radiation field value ranges in $5 \times 10^{-10} \text{ s}^{-1} \leq \beta_0 \leq 1.6 \times 10^{-8}$ s$^{-1}$ \[2\], we conclude that the UV radiation fields in the $z_{\text{abs}} = 3.025$ absorbing cloud and in the Galactic ISM are very much alike. We also found that the formation rate of H$_2$ upon grain surfaces, $R n_H \approx 3 \times 10^{-16}$ s$^{-1}$, is similar to that measured in the Galaxy \[12\].

The simultaneous analysis of metal profiles and the H+D Lyman series lines yielded a new estimation of the hydrogen isotopic ratio $D/H = (3.75 \pm 0.25) \times 10^{-5}$ in this DLA. It implies that the present-day baryon density is $\Omega_b h^2 = 0.018 \pm 0.002$. The obtained D/H value is in good agreement with the hydrogen isotopic ratio found in the Lyman Limit Systems in \[13\], \[14\], \[15\]. We thus summarize that when all most accurate measurements of D/H in high redshift QSO absorbers are considered, one finds the same D/H which is about 2.5 times the mean ISM value of $D/H = (1.50 \pm 0.10) \times 10^{-5}$ \[16\].

Recently, an attempt was made to measure $T_{\text{CMBR}}$ in the H$_2$ molecular cloud at $z = 2.34$ toward Q1232+0815 \[17\]. However, further analysis of this system \[18\] revealed inconsistency of the H$_2$ and HD column density measurements \[19\] which places the value of $T_{\text{CMBR}}$ found in \[17\] to an upper limit only.

In our analysis of the DLA system at $z = 3.025$ \[19\] we obtained a self-consistent solution for both molecular and metal absorption lines. We have considered collisions and excluded fluorescence and dust emission as significant processes in the population of the C$^+$ excited level $J = 3/2$. Our measurement of $N(\text{C}^+)/N(\text{C} \text{II}) = (3.8 \pm 0.3) \times 10^{-3}$ leads to the most probable value of $T_{\text{CMBR}} = 12.1^{+1.7}_{-3.2}$ K which is fully consistent with the predicted temperature $T_{\text{CMBR}} = 10.968 \pm 0.004$ K within 1 $\sigma$ confidence intervals.

We conclude that our result, together with upper limits measured in the
above mentioned papers support the linear evolution of the CMBR within the framework of the hot Big Bang cosmology. Being considered together, these D/H and $T_{\text{CMBR}}$ measurements show again that the fundamental concepts of cosmology and of Big Bang nucleosynthesis are consistent with observations.

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