Journal of Physics: Conference Series

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To cite this article: V V Klimenko and A V Ivanchik 2020 *J. Phys.: Conf. Ser.* **1697** 012013

International Conference PhysicA.SPb/2020 IOP Publishing
Journal of Physics: Conference Series 1697 (2020) 012013 doi:10.1088/1742-6596/1697/1/012013

The measurements of the CMB temperature in diffuse interstellar medium of the Milky-Way and high redshift galaxies based on excitation of C I fine-structure and H_2 rotational levels

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Abstract. Evolution of the cosmic microwave background (CMB) temperature with redshift $T_{\mathrm{CMB}} = T^0_{\mathrm{CMB}} \times (1+z)$ is predicted by the standard ΛCDM cosmological model and has been confirmed by measurements of the Sunyaev-Zel'dovich effect in Plank data (at $z \leq 1$) and excitation of CO rotational levels in quasar spectra (at $1.7 \leq z \leq 2.7$). Excitation of the fine-structure levels of neutral carbon (C I) is also sensitive to the temperature of the CMB radiation. However collisions and UV pumping lead to a significant degeneracy of the fitting parameters, since poor data on physical conditions. We found that a joint fit to excitation of low H_2 rotational and C I fine-structure levels can break this degeneracy and provide a tighter constraints on the T_{CMB}. We present estimates of the T_{CMB} derived from excitation of C I fine-structure levels in the Milky Way clouds and high redshift absorption systems.

1. Introduction

Temperature of the Cosmic Microwave Background (CMB) has been very precisely measured in Solar system with the space observatories experiments: Planck, WMAP and COBE/FIRAS, $T^0_{\mathrm{CMB}} = 2.72 \pm 0.03\,\mathrm{K}$ [1]. At high redshift it can be measured indirectly, and in last two decades there were many experiments aimed to estimate the CMB temperature in the early Universe. There are two different techniques: (i) at low redshift (up to $z \leq 1$) - the analysis of the thermal Sunyaev-Zel'dovich (SZ) effect towards galaxy clusters [2], (ii) at high redshift ($z > 1.7$) - the analysis of excitation of rotational levels of molecules (CO, [3,4]) and fine-structure levels of C I and C II [5,6]. It was found that the CMB temperature increases with an increase of redshift as $T_{\mathrm{CMB}} = T^0_{\mathrm{CMB}} \times (1+z)^{1-\beta}$ and the parameter β was constrained by $\beta = 0.016 \pm 0.012$ [2].

The estimate of CMB temperature with the C I excitation usually has a larger systematic uncertainty than ones with the CO. This induced by additional mechanism of excitation of fine-structure levels by collisions and UV pumping, and poor data on physical parameters of the interstellar medium (ISM) (the number density, kinetic temperature and intensity of UV field). In most cases estimates of the T_{CMB} based on the C I excitation give only upper limits (see references in [5]) or point estimates, e.g. [7,8]. Therefore C I fine-structure excitation usually used to probe physical conditions, assuming the $T_{\mathrm{CMB}}(z)$ is known. Recently it was found that a joint fit to excitation of fine-structure levels C I and rotational levels of H_2 allows one to significantly tighter constraint the UV intensity and number density [9]. Since

H_2 rotational excitation does not depend on the CMB temperature, we can use constraint on physical conditions based on the excitation of H_2 levels as a proxy distribution for estimate of the CMB temperature with the C I.

In this paper we present a systematic estimate of the CMB temperature in the cold ISM of local and high redshift galaxies based on a joint analysis of excitation of H_2 rotational and C I the fine-structure levels. In Sect. 2 we describe the method. The samples of known high C I /H_2 absorption systems are compiled in Sect. 3. In Sect. 4 we present our results.

2. Method

The neutral carbon and molecular hydrogen are known to be a good tracer of the cold diffuse phase of the ISM [10]. Observationally, C I is found to be tightly linked with H_2 [11], i.e. C I /C II transition occurs mostly in the regions where H_2 is the dominant form of hydrogen. This may be caused by enhanced absorption of C I ionized photons (IP(C I)=11.26 eV) by H_2 in transitions of Lyman and Werner bands, as well as an increase of the number density (or thermal pressure) in regions, where H_2 formed. Therefore a joint analysis of C I and H_2 excitation is likely probe the same physical region.

The determination of the physical condition of the cold diffuse ISM with the population of H_2 levels usually requires the computational expensive modelling of the cold ISM including detailed radiative transfer in resonant H_2 lines [12, 13], which are typically in optically thick regime. However, for saturated H_2 absorption systems, with $\log N(\mathrm{H_2}) > 18$, the levels of J=0,1,2 are predominantly thermalized and their excitation is typically close to the thermal temperature [14], which is set by the thermal balance, itself being a function of the density and intensity of the UV field. This makes population of rotational levels of H_2 a promising tool for estimation physical parameters in the diffuse ISM [9].

We used the PDR Meudon code [14], which performs a complete calculation of the radiative transfer of UV radiation in the UV lines of H_2 in combination with a solution of the thermal balance and chemistry. We calculated grids of constant-density model, that uniformly cover the space of three main physical parameters - the metallicity, hydrogen density and intensity of UV field. For certain absorption system we choose appropriate $I_{\mathrm{UV}} - n_{\mathrm{H}}$ grid with metallicity closest to the observed one. We found that the lower rotational levels of H_2 J=0, 1, 2 in saturated systems usually corresponds to the kinetic temperature in the cloud, and therefore obtained constraint in $I_{\mathrm{UV}} - n_{\mathrm{H}}$ plane reflects the excitation temperature T_{0-2} of H_2. In the reasonable range of number densities corresponded to the cold diffuse medium ($\log n_{\mathrm{H}} \sim 2-3$) this translates in almost linear dependence between I_{UV} and n_{H}. This dependence is usually orthogonal to the dependence obtained with the C I fine-structure excitation.

Here we briefly outline the assumptions used to analyse the C I excitation. We assumed a homogeneous medium, where C I fine-structure levels are populated by the CMB photons, UV pumping and collisions. We assumed that UV lines, at which excitation of C I fine-structure levels takes place are usually optically thin, thus we neglected the self-shielding effect for a calculation of C I UV pumping. The collisions occurs with H, H_2 and He, the collisional coefficients are taken from [15,16,17]. The number density, UV intensity, kinetic temperature and CMB temperature are the fitting parameters.

We used Monte Carlo Markov Chain calculations with an affine invariant sampler [18] to obtain the posterior probability density function (PDF) of fitting parameters. We use the likelihood for I_{UV}, n_{H} and T_{kin}, calculated with the analysis of H_2 rotational excitation as prior distributions. While we directly obtained the PDF, in the following we use the standard way of reporting the best-fitting parameters and uncertainties. The best-fitting value corresponds to the maximum posterior probability and the estimated uncertainties correspond to the 68.3 per cent confidence interval around this value (corresponding to formal 1σ uncertainty for Gaussian PDF).

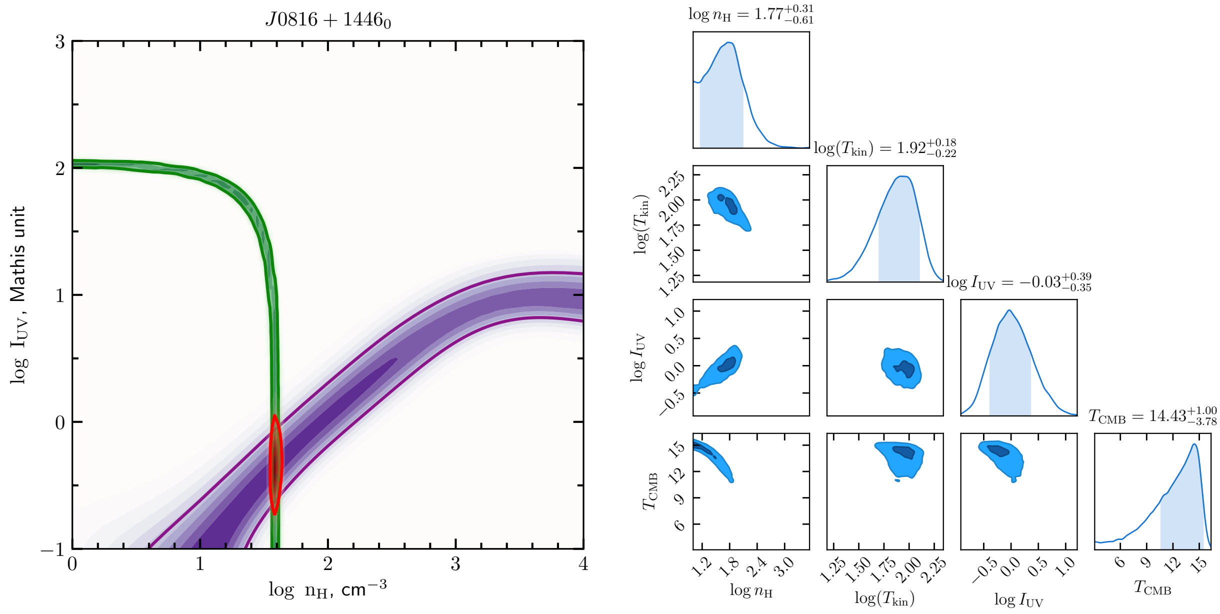

Figure 1. An example of analysis of excitation of H_2 rotational and C I fine-structure levels in the H_2 absorption systems at $z = 3.287$ towards QSO J 0816+1446. In the left panel green and purple contours represent constraints on the number density and UV intensity obtained with the analysis of excitation of fine-structure levels of C I and lower rotational levels of H_2 (J=0 to J=2), respectively. Other parameters of the fit were fixed to $T_{\rm CMB} = 11.6$ K and $T_{\rm kin} = 110$ K. Right panels: example of the 1d and 2d posterior distributions of the parameters $\log n_{\rm H}$, $\log I_{\rm UV}$, $\log T_{\rm kin}$ and $\log T_{\rm CMB}$. Dark and light blue areas in central panels respectively show the 30% and 68% confidence levels for 2D distributions. The diagonal panels indicate 1D marginalized distributions.

An example of the procedure is shown in Fig. 1 (for H_2-bearing DLAs towards quasar J 0816+1446). We estimate the CMB temperature to $14.2^{+1.3}_{-4.0}$ K at $z = 3.287$, that is in agreement with the expected $T_{\rm CMB}(z_{\rm abs}) = 11.7$ K.

3. Data

We selected eight H_2-bearing damped Lyα systems (DLAs), where C I were also detected. This DLAs have a high column density of H_2 ($\log N(H_2) > 18$), that ensures that the lower rotational levels of H_2 are self-shielded from the incident UV radiation and their populations well trace physical conditions. This sample, that we call $S^{\rm DLA}$, is presented in Table 1.

Additionally, we prepared the sample of known C I-bearing H_2 absorption systems in the Milky-Way for an additional test of our procedure. We want to be sure that obtained estimate of the $T_{\rm CMB}$ will correspond to the $T^0_{\rm CMB} = 2.72 \pm 0.03$ K [1]. Based on the results of [9] we selected four systems with low values of the number density and UV intensity. For such systems the excitation of C I fine-structure levels is more sensitive to the temperature by CMB photons. The sample, that we call $S^{\rm MW}$, is presented in Table 2.

4. Results and discussion

The estimate of the $T_{\rm CMB}$ derived from the excitation of the C I fine-structure levels in the $S^{\rm DLA}$ and $S^{\rm MW}$ samples are presented in Fig. 2 together with other measurements obtained

Table 1. The list of H_2 absorption systems included in $S^{\rm DLA}$ sample. The columns are: (1) name of QSO, (2) the redshifts of DLA, (3) total C I column density, (4) T_{01} excitation temperature of H_2, (5) hydrogen density, (6), intensity of incident UV radiation and (7) $T_{\rm CMB}$.

Name	$z_{\rm abs}$	$\log N_{\rm CI}$ [cm^{-2}]	T_{01} [K]	$\log n_{\rm H}$ [cm^{-3}]	$\log I_{\rm UV}$ [Mathis unit]	$T_{\rm CMB}$ [K]	Ref
J 0000+0048	2.525458	16.21±0.07	52±2	$1.80^{+0.18}_{-0.25}$	$0.00^{+0.42}_{-0.28}$	$6.5^{+2.7}_{-5.5}$	[20]
B 0528−2505	2.811124	12.64±0.02	167^{+15}_{-14}	$2.47^{+0.07}_{-0.08}$	$1.39^{+0.21}_{-0.23}$	$12.3^{+1.5}_{-7.2}$	[21]
J 0812+3208	2.626443	13.52±0.15	48±2	$2.55^{+0.16}_{-0.18}$	$0.04^{+0.21}_{-0.23}$	< 20	[22]
	2.626276	12.85±0.02	50^{+44}_{-16}	$1.79^{+0.24}_{-0.49}$	$-0.03^{+0.26}_{-0.20}$	$10.7^{+1.4}_{-3.2}$	
J 0816+1446	3.28742	13.67±0.02	110^{+33}_{-43}	$1.77^{+0.31}_{-0.61}$	$-0.03^{+0.39}_{-0.35}$	$14.4^{+1.0}_{-3.8}$	[23]
J 0843+0221	2.786582	13.79±0.05	123^{+9}_{-8}	$2.07^{+0.14}_{-0.16}$	$1.90^{+0.12}_{-0.13}$	< 12	[24]
J 1232+0815	2.3377	14.07±0.05	66^{+19}_{-12}	$2.03^{+0.17}_{-0.18}$	$0.02^{+0.31}_{-0.37}$	$6.8^{+2.4}_{-5.8}$	[25]
J 1513+0352	2.463622	15.02±0.05	82^{+4}_{-4}	$1.95^{+0.16}_{-0.36}$	$0.60^{+0.43}_{-0.39}$	$15.1^{+1.4}_{-7.7}$	[26]
J 2140−0321	2.3399	13.57±0.03	78^{+12}_{-9}	$2.86^{+0.23}_{-0.25}$	$1.78^{+0.25}_{-0.24}$	< 20	[27]

Table 2. The list of H_2 absorption systems included in $S^{\rm MW}$ sample. The columns are the same as in Table 1, except the redshift column that is not provided for the Milky-Way.

Name	$\log N_{\rm CI}$ [cm^{-2}]	T_{01} [K]	$\log n_{\rm H}$ [cm^{-3}]	$\log I_{\rm UV}$ [Mathis unit]	$T_{\rm CMB}$ [K]	Ref
HD27778	15.08±0.05	56^{+5}_{-5}	$2.09^{+0.15}_{-0.16}$	$-0.20^{+0.30}_{-0.28}$	$2.0^{+4.2}_{-1.6}$	[28,29]
HD40893	14.95±0.05	75^{+9}_{-8}	$1.61^{+0.04}_{-0.04}$	$-0.68^{+0.36}_{-0.25}$	$1.0^{+0.9}_{-1.5}$	[28,29]
HD185418	14.82±0.05	101^{+10}_{-8}	$1.58^{+0.08}_{-0.07}$	$-0.47^{+0.36}_{-0.31}$	$1.6^{+2.2}_{-1.3}$	[28,29]
HD192639	14.99±0.05	98^{+9}_{-9}	$1.79^{+0.07}_{-0.07}$	$-0.28^{+0.34}_{-0.31}$	$2.1^{+2.0}_{-1.8}$	[28,29]

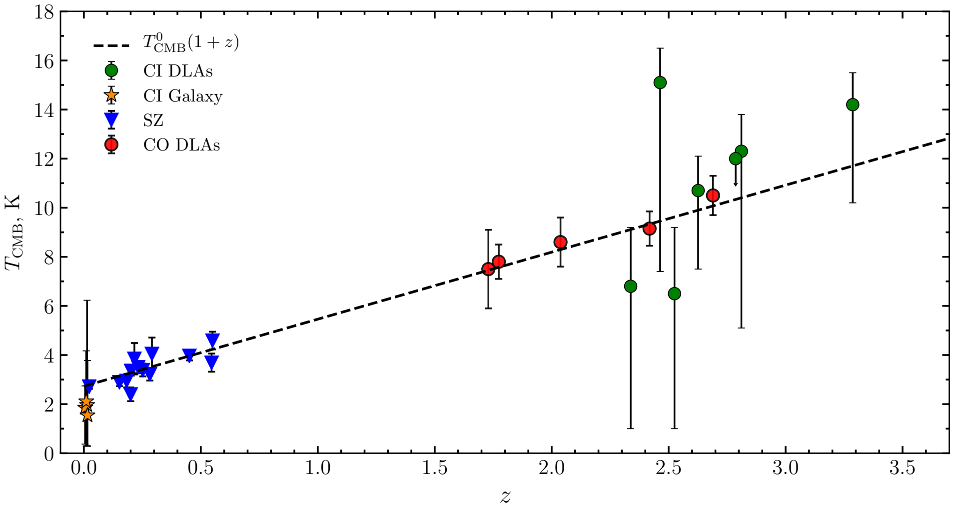

Figure 2. The measurements of the temperature of the CMB as a function of redshift. Green circle and orange squares represent measurements derived from the excitation of C I fine-structure for high redshift systems $2 < z < 3.5$ and local ones, respectively. Blue circles represent estimate of $T_{\rm CMB}$ obtained from analysis of the SZ effect [19], red circles – are the constraints from the analysis of CO molecular absorptions [3]. Dashed line represents the evolution of $T_{\rm CMB}$ expected in the standard ΛCDM model.

from excitation of CO molecules at high redshift [3] and analysis of the SZ effect for galaxy clusters [2,19].

We found an increase of the temperature of the CMB with an increase of the redshift of C I systems. The measured values of the $T_{\rm CMB}$ derived from the excitation of the C I fine-structure levels are consistent with the evolution, expected from the standard ΛCDM model. The statistical uncertainty of our estimate of $T_{\rm CMB}$ is typically higher than ones derived from the rotational excitation of CO molecules ($\Delta T \sim 1\,{\rm K}$). Nevertheless, in two out of nine systems (J0812+3208$_1$ and J0816+1446$_0$) we measured the $T_{\rm CMB}$ with an uncertainty about $\sim 2-3\,{\rm K}$. These systems have the lowest values of the number density and higher values of the redshift in our sample. The advantage of the survey of the $T_{\rm CMB}$ at high redshift with the C I absorption systems may be statistics. The cross section of the diffuse C I gas in the ISM is significantly higher than ones for translucent and dense molecular clouds.

Acknowledgments

This work is partially supported by RFBR 18-32-00701.

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