Quasar Spectroscopy and Cosmology

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Abstract. Absorption spectra of distant quasars are the main source of our knowledge of physical conditions, structures, and composition of matter in the Early Universe. The detailed analysis of such spectra gave us a possibility to discover HD/H_2 molecular clouds existed $12-13$ Gyr, investigate them and derive some important cosmological conclusions.

1. Introduction

Quasars are the most powerful sources of radiation and can be observed from distances up to $10-13$ Gyr light years. In other words, the spectra of quasars measured at the present time were formed $10-13$ Gyr ago. The emission of quasars themselves is used to probe remote clouds of interstellar and intergalactic gas along the line of sight. These clouds "imprint" their absorption lines with corresponding redshifts into the quasar spectrum. Most of the absorption lines are Lyman alpha lines at various redhshifts which are less then quasar redshift. These lines are associated with the higly ionized, high temperature intergalactic gas. Absorption systems formed in intergalactic medium can be used to probe large scale structure of the Universe. By means of correlation in Lyα forest absorptions in the spectra of distant quasars it is possible to determine Baryonic Acoustic Oscillation [1]. Some studies related to absorption lines of heavy element such as Mg II, C IV, which associated with the clouds in the halo of intervening galaxies (see e.g. [2]). Other studies are focused on Damped Ly-α systems which are thought to arise when the light from quasar pass through the intervening galaxies, and therefore provide an estimate of neutral gas density in the Universe and its evolution with time (e.g. [3]). There are also several cosmological problems that can be solved using quasar absorption system analysis: the determination of the baryon density in the Universe, the estimation of the temperature of the cosmic microwave background radiation at high redshifts, constrains on the possible variations of the fundamental physical constants and others. The first of these problems is closely related to Big Bang nucleosynthesis model.

As it is well known, at the early Universe there was a short period of synthesis of light nuclides from protons and neutrons. At that time, the Universe was filled with almost homogenous fully ionized plasma with the temperature T$\sim 10^9 - 10^8$ K. However, at that stage only the lightest nuclides D, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li and ^{7}Be could be formed in sufficient amounts. As well as the rates of relevant reactions at certain energy are well known, the relative abundance of these nuclides formed during the BBN can be reliably calculated. Left panel of Fig. 1 shows the evolution of the abundance of light nuclides with time during the BBN nucleosynthesis. The only free parameter of such calculations is $\eta = (n_B/n_\gamma)$ - the relative baryon number density n_B to the
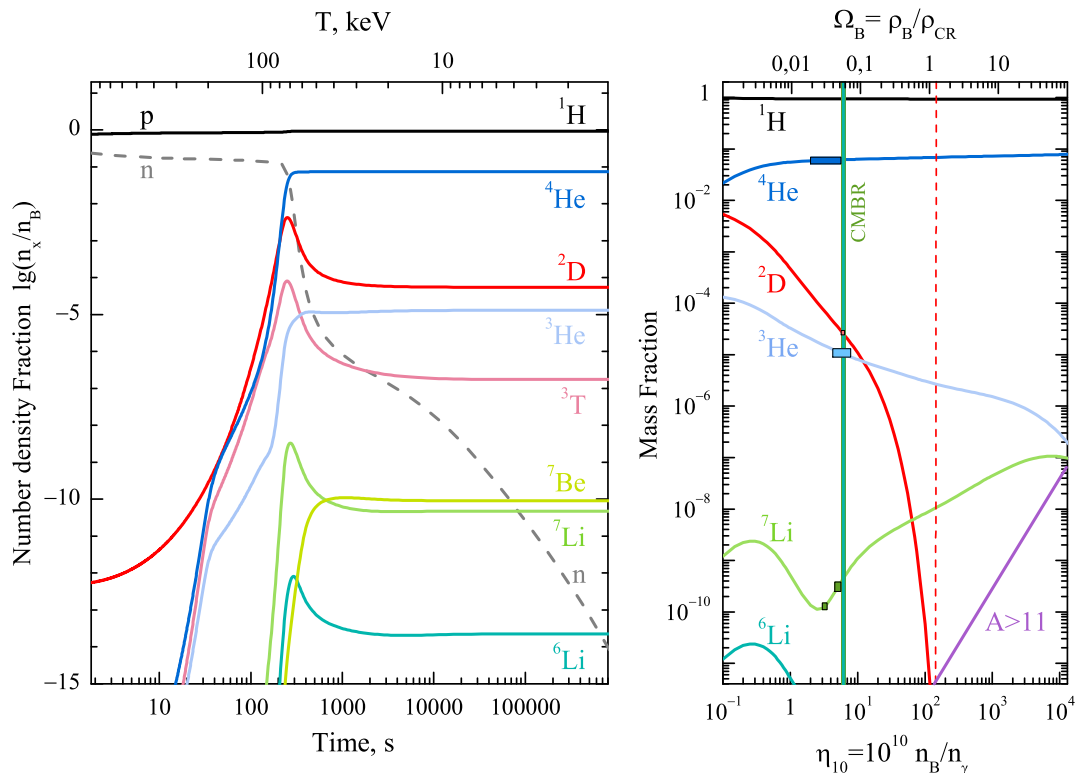
Figure 1. The results of primordial nucleosynthesis. Left panel: the evolution of abundance of light nuclides with time t and, accordingly, with the temperature T. Right panel: the relative abundance of the relic nuclides eventually formed as a function of the baryon-to-photon number density η_{10} or baryon density Ω_B. The solid lines are the theoretical calculations. The vertical strip shows the range of Ω_B obtained from different astronomical observations of primordial nuclide abundance. The dashed line corresponds to $\rho_B = \rho_{cr}$.

photon number density n_γ. This ratio has to be constant during the adiabatic expansion of the Universe. Therefore this parameter can be determined from comparison of observed abundance of primordial nuclides with the calculation results. On the right panel of Fig. 1 the dependencies of the relative abundance of light nuclides as a function of the $\eta_{10} = 10^{10}\eta$ (or the $\Omega_B = \rho_B/\rho_{cr}$ – baryon density ρ_B in units of critical density ρ_{cr}) are presented. It is clearly seen that the relative abundance of primordial deuterium $(D/H)_p$ is the most sensitive to the baryon number density. For example, if the density of baryon matter were equal to the critical one $\rho_B = \rho_{cr}$, we would not observe primordial deuterium at all. The isotopic abundance ratio (D/H) could only decrease during the subsequent evolution of the Universe because deuterium rapidly burns out into helium in stellar interiors. Therefore to infer baryon number density from (D/H) ratio, it is necessary to determine isotopic composition of the interstellar or intergalactic medium at as early cosmological epoch as possible, when the composition was close to the primordial one.

Until very recently, the relative abundance of (D/H) at high redshifts was measured using only atomic HI and DI by means of Lyman series lines detected in quasar absorption spectra [4]. However, such measurement encounters with severe obstacles. The spectra of HI and DI are virtually the same, with only all wavelengths are shifted at about 81 km/s. This value is closed to the typical velocity offset between multiply components seen in quasar absorption
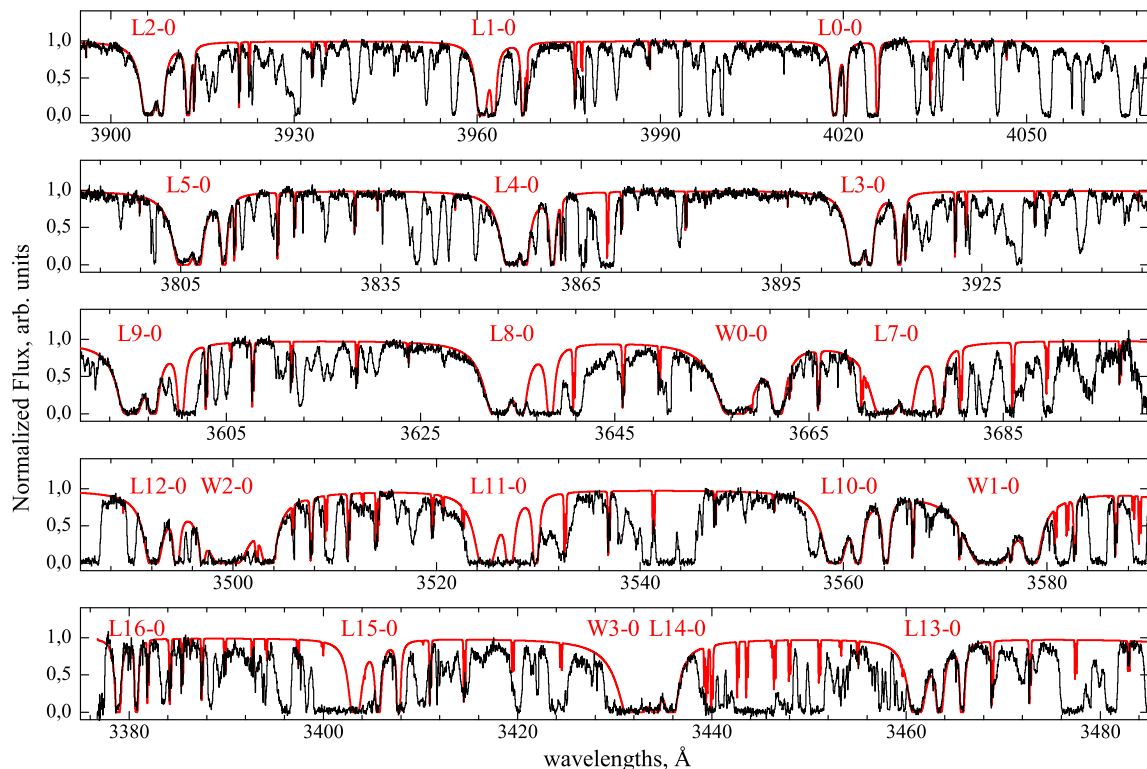
Figure 2. The high resolution optical spectrum of Q 0812+320 obtained at KECK telescope. Synthetic H_2 spectrum of the absorption system at z = 2.62649 fitted into the observed spectrum shown by red line. The bands of Lyman and Werner series of H_2 are marked.

spectra, which is believed to be several clouds on the line of sight located in gravitationally bounded systems like galaxy or protogalaxy. Also number density of DI is lower by 4-5 order of magnitude relative to HI, that makes line profile analysis very complicated. These facts can possibly explain the significant dispersion of values of the (D/H) ratio measured by atomic lines.

Difficulties with line identification did not arise in measurement of the relative abundance of HD and H_2 molecules, since their spectra are significantly differs and most of absoprtion lines are much narrow then atomic one. This methods applied only recently with first detection of HD molecules at high redshifts [5].

2. HD/H_2 absorption systems
One kind of absorption systems identified in quasar spectra are the molecular hydrogen absorption systems, which are very rare detected in quasar spectra. Only in < 1% of quasar spectra it is possible to detect H_2 absorption system. Additionally, H_2 absorption system can be identify only in high resolution spectra (R~50000), which is available only on the biggest optical telescope like Very Large Telescope and KECK. Molecular hydrogen absorption systems are supposed to be a diffuse interstellar clouds located in the intervening galaxy. These remote galaxies are detected in quasars spectra as Damped Lyman alpha (DLA) systems - absorption systems with damped Lyman alpha line, with column density of neutral hydrogen log(N)> 10^{20}cm^{-2}. This amount of neutral hydrogen is sufficient to shield medium from diffuse cosmic UV background. Analysis of H_2 absorption systems allows us to study the physical conditions of diffuse clouds in remote galaxies. Numerous absorption lines of molecules H_2, in
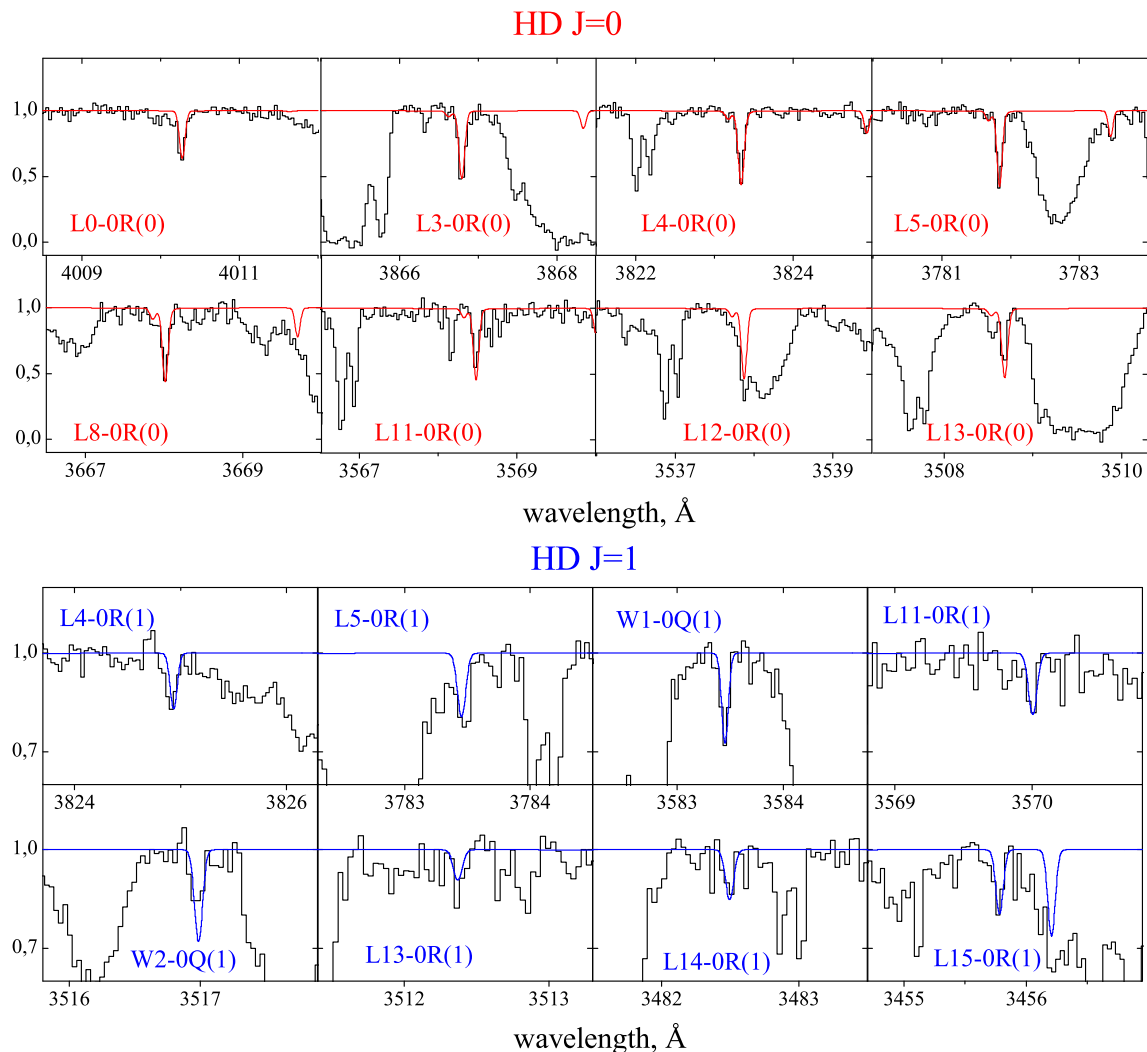
Figure 3. HD absorption lines, associated with H_2 absorption system at z=2.62649 in spectrum of Q 0812+320. Top and bottom panels show absorption lines for J=0 and J=1 level, respectively.

some cases HD and CO, and metals in different ionization states show that this cloud have typical temperatures $\sim 10 \div 100$ K and number densities in range $\sim 1 - 100\, cm^{-3}$. There are indications that size of these clouds are about parsec and subparsec, that is well agreed with what observed in nearby galaxies.

To date there are only 24 H_2 absorptions systems detected at high redshifts. Only in 6 of them have HD absorption lines. The detected HD/H_2 absorption systems are shown in Table 1. Fig. 2 shows spectrum of Q 0812+320 (obtained at 10 meter optical KECK telescope with high resolution spectrograph HIRES), in which one of the H_2 absorption system was detected [6] and it is shown by red profiles. Numerous (up to 80) absorption lines of H_2 from different rotational levels were detected in this systems. This allows us to obtain H_2 column density of this absorption system with great accuracy. Later, HD molecules were detected in this system [7], [8]. Some of the detected HD lines are shown on Fig. 3. The column densities of HD molecules are presented in Table 1. Additionally HD absorption lines corresponding J=1 rotational levels (see lower panels on Fig. 3) were detected in this system for the first time at high redshift.

Table 1. List of known HD/H_2 absorption systems at high redshifts detected in quasars spectra. R_{mag} is the magnitude of QSO. z_{abs} and z_{em} - are the redshifts of absorption system and quasar, respectively. $N(H I)$, $N(H_2)$ and $N(HD)$ - are log of the column densities (in cm^{-2}) of neutral hydrogen, H_2 and HD molecules of absorption systems, respectively.

Quasar	R_{mag}	z_{abs}	z_{em}	$N(H I)$	$N(H_2)$	$N(HD)$	reference
Q 0812+320	17.88	2.63	2.70	21.4	19.9	15.4	[7], [8]
Q 1232+082	18.40	2.34	2.57	20.9	19.7	15.5	[9], [10]
Q 1331+170	16.26	1.78	2.08	21.2	19.7	14.8	[11], [7]
Q 1439+113	18.07	2.42	2.58	20.1	19.4	14.9	[12]
J 1237+064	18.21	2.69	2.78	20.0	19.2	14.5	[13]
J 2123−005	15.83	2.06	2.26	19.2	17.6	13.8	[14]

H_2 and HD molecules are easily destroyed by the ultraviolet radiation. After absorbing UV photon in Lyman and Werner bands molecular hydrogen gets to the excited electronic states. Then it quickly returns in the electronic ground state. However about 13% of molecules fall in the continuum of ground electronic state, i.e. dissociated. When UV radiation penetrates into the cloud, Lyman and Werner lines becomes saturated, and rate of excitation decreases, therefore the rate of photodissociation decreases too. Calculation shows that at column density $N > 10^{15}$ cm^{-2} HD (as well as H_2) molecules are effectively shield itself from destructive UV radiation. Models of HD/H_2 clouds [15] demonstrate that in case of self-shielding all D will be in form of HD and all H will be in form of H_2. Therefore, for the self-shielded clouds the ratio of column densities $N(HD)/2N(H_2)$ is well agreed with isotopic D/H ratio.

From 6 known HD/H_2 absorption systems we selected two systems corresponding the condition of self-shielding: z=2.33771 in spectrum of Q 1232+082 and z=2.62649 towards Q 0812+320. The abundance of heavy elements (obtained from measurement of associated absorption lines) was found to be about an order magnitude less then the solar one. It may indicate that these identified clouds have composition close to the primordial one. We have estimated D/H isotopic ratio for these clouds by using $N(HD)/2N(H_2)$ ratio. It is consistent with the values of D/H determined from analysis of atomic D I and H I lines and the value obtained from analysis of the Cosmic Microwave Background fluctuations.

3. Conclusions

We have found for the first time [5] and investigated high-redshift molecular clouds containing HD as well as H_2 molecules, which existed at early cosmological epoch, 12-13 Gyr ago. The composition of these HD/H_2 clouds and the proper physical conditions were determined. Obtained low abundance of element heavier then H and He indicates that their composition were almost the primordial one. The typical value of abundance of heavy elements is one order lower then the solar abundance.

D/H isotopic ratio that existed in such clouds 12-13 Gyr ago has been estimated by new method – from abundance of HD to H_2 molecules. This ratio can be derived only for absorption systems with high HD column density, which corresponds condition that in the cloud all D is in form of HD and all H in form of H_2. From two HD/H_2 systems with higher HD molecules column density at z=2.33771 at spectrum of Q 1232+082 and z=2.62649 at Q 0812+320 spectrum we
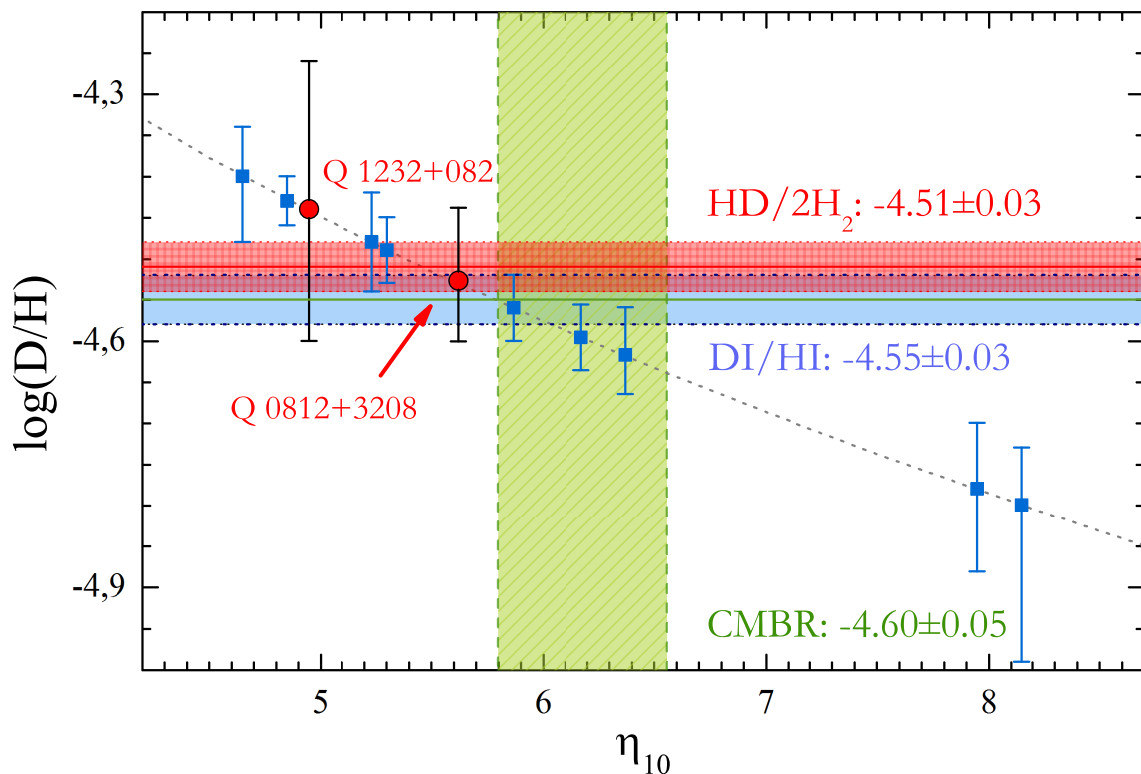
Figure 4. The results of the measurements of the isotopic D/H ratio at high redshifts. The blue points correspond to the atomic D I to H I absorption lines observed in quasar spectra. The two red points are the measurements of D/H isotopic values derived from the analysis of HD/H_2 absorption systems identified in Q 1232+082 and Q 0812+320. The blue and red horizontal stripe is mean values for blue and red points, respectively. The dotted line shows the dependence of D/H ratio as a function of η_{10} inferred from BBN. The green vertical strip is the value obtained from the analysis of the Cosmic Microwave Background fluctuations.

derived

$$D/H = N(\mathrm{HD})/2N(\mathrm{H_2}) = 2.97^{+0.52}_{-0.50} \times 10^{-5}$$

The baryon fraction in the Universe has been estimated from D/H isotopic ratio obtained on the base of the standard model of Big-Bang Nucleosynthesis, as we believed that all deuterium was formed just through this process

$$\Omega_B(\mathrm{BBN}) = \rho_b/\rho_{cr} = 4.1 \pm 0.3\%$$

This value of Ω_B (within errors) is consisted with value obtained from Cosmic Microwave Background fluctuations [16]

$$\Omega_B(\mathrm{CMB}) = \rho_b/\rho_{cr} = 4.6 \pm 0.3\%,$$

although the corresponding epochs are quite different.

Thus high resolution spectroscopy of high redshifted astrophysical objects may be a high-way to the fundamental cosmological parameters.

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