

CONFERENCES AND SYMPOSIA

PACS numbers: 01.10.Fv, **26.30.–k**, **26.35.+c**, **95.35.+d**, **95.36.+x**, 95.55.Ka, 95.85.Pw, 98.38.Dq, 98.62.Hr, **98.65.–r**, 98.70.Rz, 98.80.Cq

Extragalactic astronomy
(Scientific session of the Physical Sciences Division of the Russian Academy of Sciences, 28 October 2009)

DOI: 10.3367/UFNe.0180.201004e.0415

A scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS), "Extragalactic astronomy," was held in the Conference Hall of the Kapitza Institute for Physical Problems, RAS, on 28 October 2009.

The following reports were put on the session agenda posted on the web site www.gpad.ac.ru of the Physical Sciences Division, RAS:

(1) **Varshalovich D A, Ivanchik A V, Balashev S A** (Ioffe Physical Technical Institute, RAS) "Big Bang nucleosynthesis of deuterium and HD/H_2 molecular abundances in interstellar clouds of 12 Gyr ago";

(2) **Aptekar R L, Golenetskii S V, Mazets E P** (Ioffe Physical Technical Institute, RAS) "Studies of cosmic gamma-ray bursts and gamma repeaters with the Ioffe Institute Konus experiments";

(3) **Beskin G M, Karpov S V** (Special Astrophysical Observatory, RAS), **Bondar S V** (Scientific Research Institute of Precision Instrument Making) "Discovery of the fast optical variability of the GRB 080319B gamma burst and the prospects for wide-angle high time resolution optical monitoring";

(4) **Starobinskii A A** (Landau Institute for Theoretical Physics, RAS) "Experimental and theoretical investigation of dark matter in the Universe";

(5) **Zasov A V, Sil'chenko O K** (Shternberg State Astronomical Institute, Lomonosov Moscow State University) "Galactic disks and their evolution";

(6) **Burdyuzha V V** (Astro-Space Center of the Lebedev Physics Institute) "Dark components of the Universe."

Papers based on reports 1–3, 5, and 6 are published below. A A Starobinskii's extended report will be presented in the form of a review, which is planned for publication in one of the forthcoming issues of *Physics–Uspekhi*.

Uspekhi Fizicheskikh Nauk **180** (4) 415 – 444 (2010)
DOI: 10.3367/UFNr.0180.201004e.0415
Translated by R L Aptekar, K A Postnov, E N Ragozin; edited by A M Semikhatov

PACS numbers: **26.30.–k**, **26.35.+c**, 98.38.Dq
DOI: 10.3367/UFNe.0180.201004f.0415

Big Bang nucleosynthesis of deuterium and HD/H_2 molecular abundances in interstellar clouds of 12 Gyr ago

D A Varshalovich, A V Ivanchik, S A Balashev, P Petitjean

1. Big Bang nucleosynthesis

It has been widely discussed recently that previously unknown forms of matter and energy, cold dark matter (CDM) and dark energy (DE), dominate in the Universe, while ordinary baryonic matter (consisting of protons and neutrons) contributes only 4–5% to the total energy density. This statement is based on the detailed quantitative analysis of the Big Bang nucleosynthesis (BBN) and careful measurement of the deuterium abundance in the interstellar matter of the most distant galaxies and protogalaxies [1, 2].

As is well known, there was a short stage in the early Universe when the temperature decreased such that the synthesis of nuclides from protons and neutrons became effective. At that time, the Universe was a unique thermonuclear reactor filled with almost homogeneous fully ionized plasma with the temperature $T \sim 10^9 - 10^8$ K. But that stage was so short that only the lightest nuclides ^{2}D, ^{3}T, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li, and ^{7}Be could be formed in appreciable amounts. The relative abundance of relic nuclides formed during BBN can be reliably calculated because the rates of all relevant reactions are well known. The relative baryon number density is the only free parameter. This parameter can be determined from comparison of the results of calculations with astronomical observations of the abundance of relic nuclides.

Figure 1a shows the change in nuclide composition with time t and temperature T, which at that time were related as $t = AT^{-2}$, where the coefficient A is determined by the effective number of the degrees of freedom of ultrarelativistic

D A Varshalovich, A V Ivanchik Ioffe Physical Technical Institute, Russian Academy of Sciences, St. Petersburg, Russian Federation
E-mail: varsh@astro.ioffe.ru
Saint Petersburg State Polytechnic University, St. Petersburg, Russian Federation
S A Balashev Ioffe Physical Technical Institute, Russian Academy of Sciences, St. Petersburg, Russian Federation
P Petitjean Institut d'Astrophysique de Paris, France

Uspekhi Fizicheskikh Nauk **180** (4) 415 – 420 (2010)
DOI: 10.3367/UFNr.0180.201004f.0415
Translated by K A Postnov; edited by A M Semikhatov

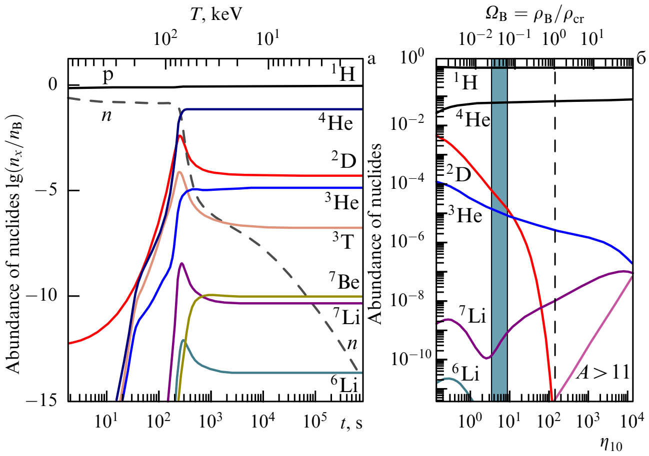

Figure 1. Primordial nucleosynthesis. (a) Change in the composition of matter with time t and, accordingly, with the temperature T. (b) The relative abundance of the relic nuclides eventually formed as a function of the baryon-to-photon number density ratio $\eta_{10} = 10^{10}(n_B/n_\gamma)$. The solid lines show the theoretical calculations, the dark vertical strip indicates the range of η_{10} obtained from different astronomical observations of the relic nuclide abundance, and the dashed line corresponds to $\rho_B = \rho_{cr}$.

particles (photons, neutrinos, and antineutrinos of all flavors).

Figure 1b presents the results of calculations of the final abundance of relic nuclides as a function of the baryon-to-photon number density ratio n_B/n_γ. The dark strip in the figure shows the n_B/n_γ range corresponding to astronomical measurements of the relative abundance of relic nuclides. It can be seen from this figure that the relative abundance of primordial deuterium $(D/H)_p$ is the most sensitive indicator of the baryon-to-photon number density ratio n_B/n_γ. For example, if the density of baryonic matter were equal to the critical one, $\rho_B = \rho_{cr}$, we would not observe primordial deuterium at all, because its abundance would be eight orders of magnitude smaller than the present value.

The isotopic ratio D/H could only decrease in the course of the subsequent evolution, because deuterium rapidly burns out into helium in stellar interiors. Therefore, to determine $(D/H)_p$, the isotopic composition of the interstellar medium should be measured at as early a cosmological epoch as possible. The absorption spectra of high-redshift quasars are the most appropriate. Quasars are the most powerful sources of radiation, and can be observed from distances up to 10–12 bln light years. In other words, the spectra of quasars measured at the present time were formed 10–12 Gyr ago. The emission of quasars themselves is used to probe remote clouds of interstellar and intergalactic gas along the line of sight, which 'imprint' their absorption lines into the quasar spectrum. It can be said that quasars serve as an 'X-ray device' to shine through the Universe.

Until recently, the relative abundance of D/H was measured using only atomic lines of H I and D I in quasar absorption spectra. However, such measurements met with some difficulties. Optical spectra of H I and D I are virtually the same, with all wavelengths being slightly shifted by 0.027%. But the number densities of these atoms differ by 4–5 orders of magnitude, and hence if the column density along the line of sight of H I atoms is small, D I lines cannot be seen at all. If the hydrogen column density is too high, H I lines are saturated, broadened, and blended with D I lines. Moreover, the lines identified as D I lines can in principle originate from a small H I cloud moving relative to the cloud under study with a speed ~ 80 km s^{-1}; many such clouds moving with different speeds are indeed found along the line of sight (the so-called Lyman-alpha forest). The significant dispersion of values of the D/H ratio measured this way can possibly be explained by these facts (see Section 3, Fig. 5).

Difficulties in the line identification would not emerge in measurements of the relative abundance of HD and H_2 molecules because their spectra are significantly different and most absorption lines are unblended. This method has not been used until recently because no HD molecules have been found at high redshifts.

2. An HD/H_2 cloud with the redshift $z = 2.33771$

We were the first to discover hydrogen deuterium molecules at high redshifts. The HD lines were identified in the absorption spectrum of quasar Q 1232+082 redshifted such that $\lambda_{obs}/\lambda_{em} = 1 + z = 3.337714(3)$ [3]. In fact, a cloud containing HD molecules along with H_2 was first discovered at a large cosmological distance. This cloud existed about 12 Gyr ago, when neither the Solar System nor our Galaxy had formed.

Figures 2 and 3 show the scheme of energy levels and the Lyman series transitions $Lv'' - 0$ of H_2 and HD molecules and parts of the quasar spectra with the corresponding lines. For HD, R_0 lines corresponding to transitions from the ground state $J = 0$ are visible, while for H_2, lines corresponding to transitions from the ground state of para-H_2 ($J = 0$), ortho-H_2 ($J = 1$), and excited rotational states R_J and P_J with $J = 2, 3, 4, 5$ are also seen, because the lifetimes τ_J of H_2 molecules in these states are orders of magnitude longer than this time for HD molecules.

After additional careful measurements of these quasar spectra carried out by French colleagues on the 8.2 m VLT (Very Large Telescope) of the European Southern Observatory (ESO) in Chile, we have determined the column number densities of HD and H_2 molecules in this cloud: $N(\text{HD}) = (3.4^{+1.6}_{-0.8}) \times 10^{15}$ cm^{-2} and $N(H_2) = (4.8 \pm 1.0) \times 10^{19}$ cm^{-2} [4]. The HD/H_2 column number density ratio turned out to be $(7.1^{+3.7}_{-2.2}) \times 10^{-5}$. This value significantly exceeds those measured in interstellar clouds of our Galaxy, $(0.4-4.0) \times 10^{-6}$ [5]. Figure 4 shows the obtained spectrum of quasar Q 1232+082 [4] in comparison with the absorption spectrum of ζ Oph [6], which is typical for an interstellar molecular cloud in our Galaxy. Both spectral fragments correspond to the same comoving wavelength range, but the quasar spectrum is observed redshifted 3.33771-fold. The comparison of spectra demonstrates that the relative abundance of HD/H_2 molecules in the cosmological cloud that existed 12 Gyr ago is much higher than the present-day value. A quantitative estimate gives a 200-fold difference.

The analysis of the obtained spectrum revealed that this cloud does contain a small amount of matter processed in stars, i.e., deuterium deficient. This is evidenced by the presence of certain spectral lines, in particular, the Ar I line shown in Fig. 4. The quantitative analysis in [7] demonstrated that the elemental abundance of such species as Si, P, S, Ar, and Ti is 30–40 times smaller than the solar one. For example, the abundance of Ar in the cloud amounts to $(2.4^{+1.9}_{-1.0})$% of the solar value. In the protosolar nebula, the D/H ratio was estimated to be 1.94×10^{-5} [8], i.e., differed from the primordial value by 30–50%, and hence there are grounds to believe that the D/H ratio in the

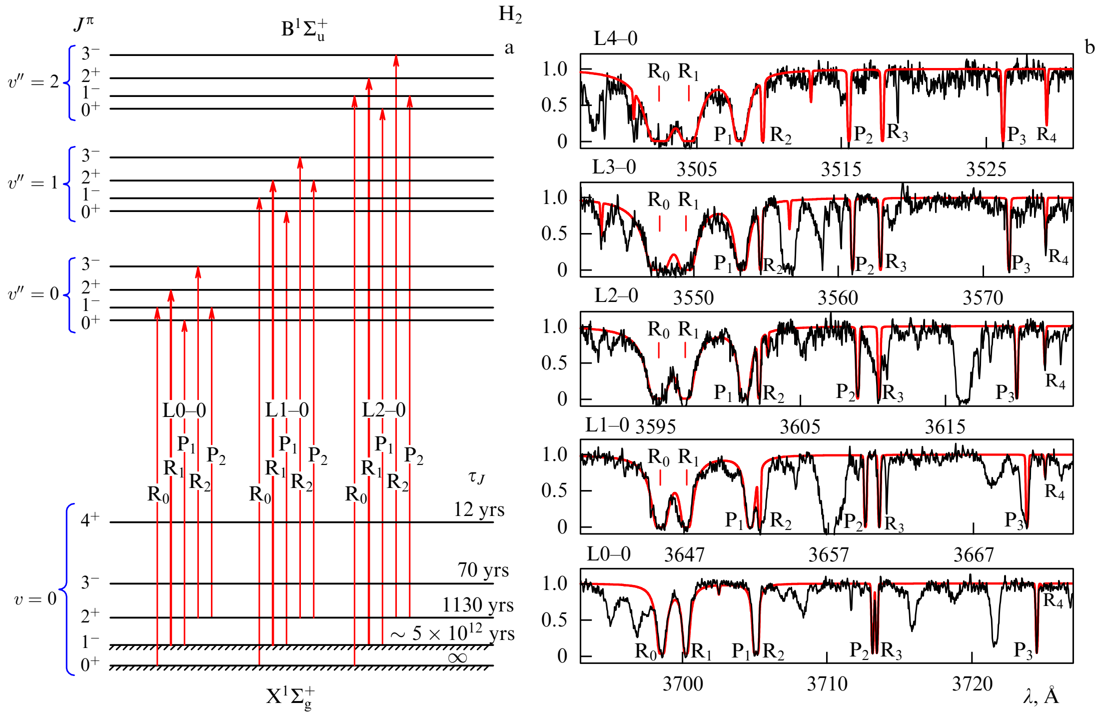

Figure 2. (a) Scheme of the Lyman series levels and $\mathrm{L}v''-v$ transitions in H_2 molecules. (b) Parts of the spectrum of Q 1232+082 quasar in which the corresponding H_2 absorption lines are seen, with wavelength cosmologically redshifted as $\lambda_{obs}/\lambda_{em} = 3.33771$.

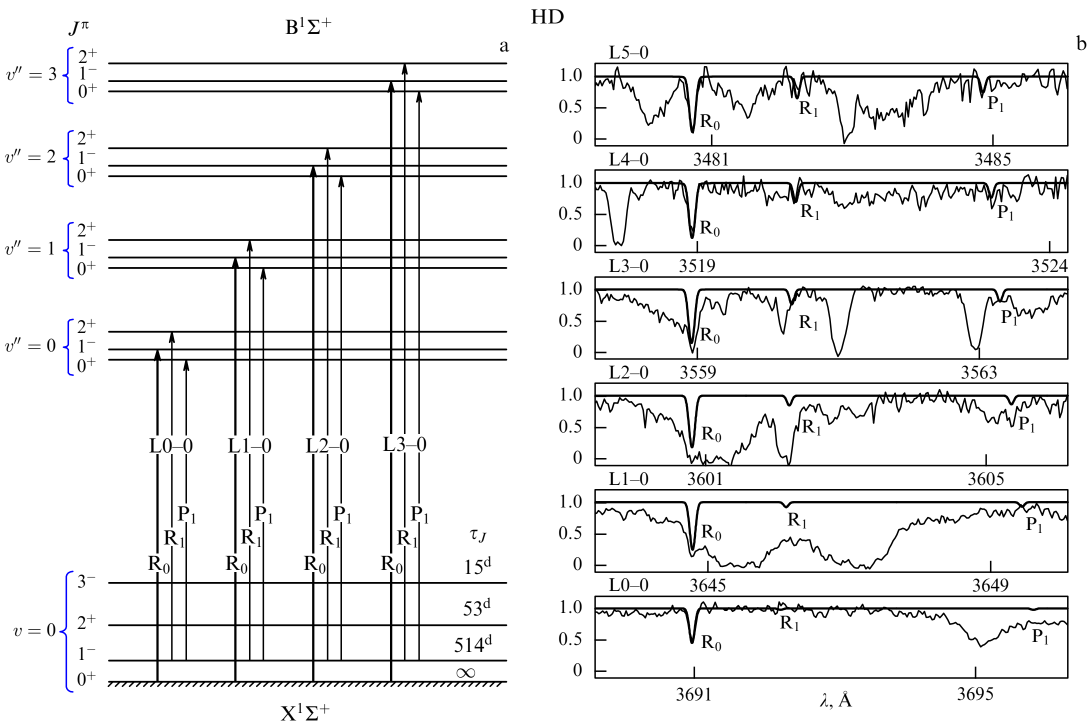

Figure 3. (a) Scheme of levels and transitions in HD molecules. (b) Parts of the spectrum in which HD lines are redhsifted as $\lambda_{obs}/\lambda_{em} = 3.33771$.

studied cosmological cloud differs from the primordial value $(D/H)_p$ by only 1–2%.

Therefore, the studied absorption system represents a cold rarefied cloud of interstellar gas in a remote galaxy or protogalaxy. The kinetic gas temperature inferred from the relative abundance of ortho- and para-H_2 is $T = 67 \pm 11$ K. The mean gas number density derived from the relative populations of the fine-structure levels of C I is (71 ± 28) cm^{-3}. The size of the cloud is estimated to be about one pc. Spectral analysis showed that O I, N I, and Ar I atoms with an ionization potential higher than 13.6 eV are present in the cloud only in neutral states, while C, Mg, Al, Si, P, S, Ti, Mn, and Fe with an ionization potential lower than 13.6 eV are present as neutral and single-ionized atoms (predominantly). This fact allows estimating the flux of ionizing ultraviolet (UV) radiation in the cloud. The radia-

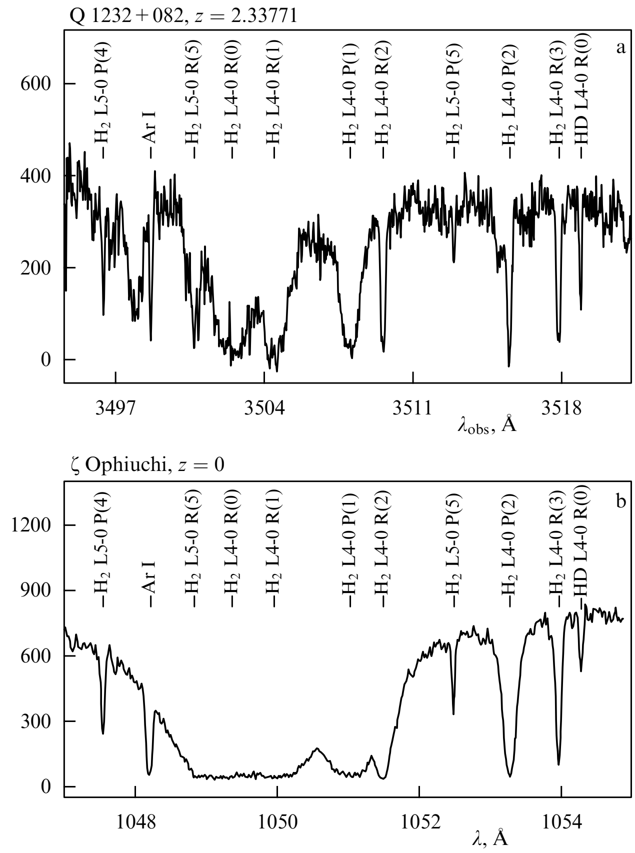

Figure 4. The spectrum of quasar Q 1232+078 [4] in comparison with the absorption spectrum of ζ Oph [6], which is typical for interstellar molecular clouds in our Galaxy. Both spectral fragments correspond to the same wavelength range in the comoving reference system, but the wavelength scale is redshifted 3.33771-fold for an astronomer on Earth. The comparison of spectra shows that the relative abundance of HD/H_2 molecules in the cloud that existed 12 Gyr ago was significantly higher than the present-day value.

tion transfer in H_2 lines in the studied cloud is treated in detail in paper [9].

Thus, detailed analysis of the obtained spectrum allowed us to reveal evolutionary changes in the chemical and isotopic composition of matter over 12 Gyr and to determine the physical conditions in the cloud at that time.

3. Relative abundance of D/H isotopes and baryonic content

To determine the abundance of the isotope ratio D/H from the relative abundance of HD/H_2 molecules, it is necessary in general to consider all channels of creation and destruction of these molecules. The dominating destruction channel of H_2 and HD molecules is due to dissociation by UV radiation in resonance lines. The UV radiation excites molecules from the ground state $X^1\Sigma_g^+$ to upper electronic states $B^1\Sigma_u^+$ and $C^1\Pi_u$, i.e., the excitation occurs in lines of the Lyman and Werner bands in the 1120–912 Å wavelength range (just these lines are observed in quasar spectra). About 87% of the molecules excited by UV radiation return to the ground electron state (to different vibration–rotational levels) and about 13% of the molecules dissociate. But radiation in the cloud is absorbed in lines of the Lyman and Werner series, and the lines saturate, and hence H_2 and HD molecules inside the cloud are shielded from the destroying action of UV radiation. The self-shielding of the cloud begins when the optical depth in resonance lines increases to unity, which corresponds to the molecular column density $\sim 4 \times 10^{14}$ cm^{-2}. In our case, the measured column density of H_2 and HD molecules is far above this threshold. Under such conditions, calculations of interstellar molecular clouds [10–12] show that virtually all gas must be molecularized, i.e., all D must be in the form of HD molecules and all H in the form of H_2 molecules. In this case, the universal relation $HD/H_2 = 2(D/H)$ sets in. This fact allowed us to determine the isotopic ratio in the cloud: $D/H = (3.6^{+1.9}_{-1.1}) \times 10^{-5}$ [4].

The obtained value of D/H is compared with results of other studies in Fig. 5, in which deuterium and other relic

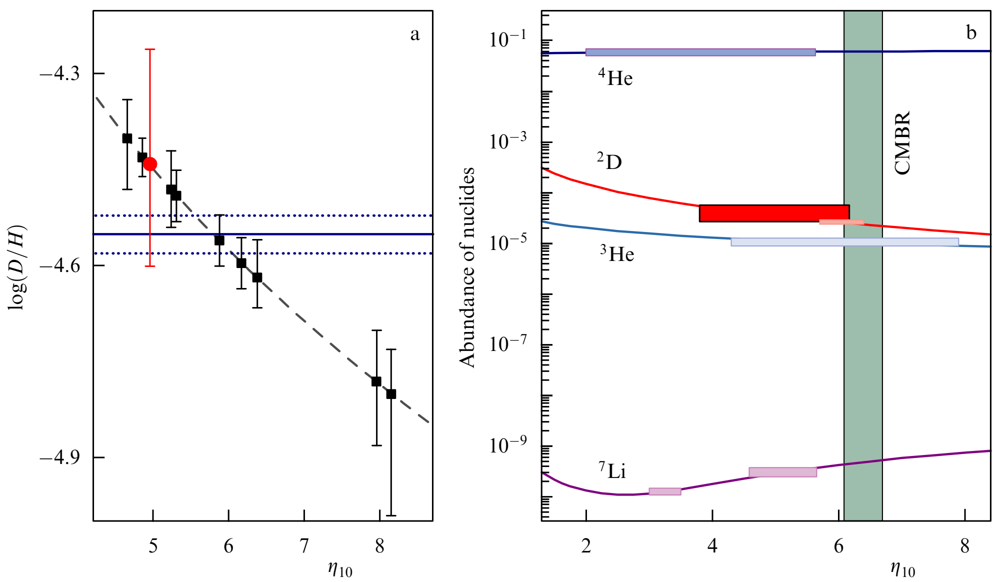

Figure 5. The relative abundance of deuterium and other relic nuclides as a function of the relative baryonic number density $\eta_{10} = 10^{10}(n_B/n_\gamma)$. (a) The results of measurements of D/H in quasar spectra using absorption lines of D I/H I atoms (the filled squares) and HD/H_2 molecular lines (the filled circle) [4]. (b) The results of measurements of the relative abundance of relic nuclides compared with theoretical curves and with the value n_B/n_γ obtained from a CMB anisotropy analysis [13].

nuclide abundance is plotted as a function of the relative baryon-to-photon number density ratio n_B/n_γ. Figure 5a demonstrates the value of (D/H) measured in quasar spectra from absorption lines of D I/H I atoms and from HD/H_2 molecular lines (see [4] for data and references). In Fig. 5b, the results of measurements of the relative abundance of relic nuclides ^{2}D, ^{3}He, ^{4}He, and ^{7}Li are compared with theoretical calculations and with the n_B/n_γ ratio derived from the analysis of angular fluctuations of the CMB temperature [13].

With the obtained value of (D/H), the BBN theory implies the baryon-to-photon number density ratio $n_B/n_\gamma = (5 \pm 1) \times 10^{-10}$ [4]. In calculating the kinetics of the primordial nucleosynthesis, we have used a modified code developed in [14, 15]. According to the standard cosmological model, the n_B/n_γ ratio should not have changed from BBN times to the present day, i.e., it is assumed that baryons have not decayed and CDM particles have not been converted into baryons. At present, the CMB photon number density corresponding to the temperature $T_0 = 2.726$ K is $n_\gamma = 411$ cm^{-3}. Therefore, the mean baryon number density must be $n_B(0) = (2.1 \pm 0.4) \times 10^{-7}$ cm^{-3}. But in contrast to the BBN epoch when the medium was almost homogeneous, the present-day space matter distribution is highly inhomogeneous, and hence $n_B(0)$ is the mean value in a large space region of the order of 100 Mpc. The obtained value $n_B(0)$ corresponds to $(3.7 \pm 0.8)\%$ of the critical density (for the assumed Hubble constant $H_0 = 70$ km s^{-1} Mpc^{-1}). This is consistent within error with the value obtained from the CMB temperature fluctuations [13].

4. Conclusion

For the first time, a cloud of cold rarefied gas containing H_2 and HD molecules was discovered at a large cosmological distance. The elemental abundance and physical conditions in the cloud that existed 12 Gyr ago have been studied. The column density ratio HD/H_2 in the cloud is shown to be much higher than the present-day value measured in interstellar clouds of our Galaxy [4].

The relative isotopic abundance D/H in this cloud was measured by a novel (independent) method from the column density ratio of HD/H_2 molecules using molecular cloud models [10–12]. The derived value $D/H = (3.6^{+1.9}_{-1.1}) \times 10^{-5}$ and the standard BBN model allowed an independent determination of the mean baryonic density at the present time $\Omega_B \equiv \rho_B/\rho_{cr} = (3.7 \pm 0.8)\%$ [4].

This work was supported by the Program of the Presidium of the Russian Academy of Sciences "Origin, Structure, and Evolution of Objects in the Universe," the Russian Foundation for Basic Research grant No. 09-02-01264a, and grant NSh-3769.2010.2.

References

1. Steigman G *Annu. Rev. Nucl. Part. Syst.* **57** 463 (2007)
2. Pettini M et al. *Mon. Not. R. Astron. Soc.* **391** 1499 (2008)
3. Varshalovich D A et al. *Pis'ma Astron. Zh.* **27** 803 (2001) [*Astron. Lett.* **27** 683 (2001)]
4. Ivanchik A V et al. *Mon. Not. R. Astron. Soc.* **404** 1583 (2010), doi: 10.111/j.1365-2966.2010.16383.x; arXiv:1002.2107
5. Lacour S et al. *Astron. Astrophys.* **430** 967 (2005)
6. Spitzer L (Jr.), Jenkins E B *Annu. Rev. Astron. Astrophys.* **13** 133 (1975)
7. Balashev S A et al, in preparation
8. Lodders K, Palme H, Gail H-P, in *Landolt-Börnstein, New Series. Astronomy and Astrophysics* (Berlin: Springer-Verlag) (in press); arXiv:0901.1149
9. Balashev S A, Varshalovich D A, Ivanchik A V *Pis'ma Astron. Zh.* **35** 171 (2009) [*Astron. Lett.* **35** 150 (2009)]
10. Abgrall H et al. *Astron. Astrophys.* **253** 525 (1992)
11. Le Bourlot J *Astron. Astrophys.* **360** 656 (2000)
12. Le Petit F, Roueff E, Le Bourlot J *Astron. Astrophys.* **390** 369 (2002)
13. Komatsu E et al. *Astrophys. J. Suppl.* **180** 330 (2009); arXiv: 0803.0547
14. Orlov A V, Varshalovich D A "Kinetika pervichnogo nukleosinteza: novyi paket programm" ("Kinetics of the primordial nucleosynthesis: a new code"), Preprint FTI No. 1719 (St. Petersburg: FTI RAN, 1999)
15. Ivanchik A V, Orlov A V, Varshalovich D A *Pis'ma Astron. Zh.* **27** 723 (2001) [*Astron. Lett.* **27** 615 (2001)]

PACS numbers: 95.55.Ka, 95.85.Pw, 98.70.Rz
DOI: 10.3367/UFNe.0180.201004g.0420

Cosmic gamma-ray bursts and gamma repeaters studies with Ioffe Institute Konus experiments

R L Aptekar, S V Golenetskii, E P Mazets, V D Pal'shin, D D Frederiks

This report presents the results of the study of cosmic gamma-ray transients, performed for many years by the Ioffe Institute onboard interplanetary space missions and near-Earth satellites. These transients have been found in several classes: many of the basic characteristics of cosmic gamma-ray bursts (GRBs), such as their temporal profiles and energy spectra, and the first all-sky map of their source distribution on the celestial sphere, were determined using early Konus experiments onboard the Venera 11, 12, 13, and 14 deep space vehicles. As a result of the observations of the giant flare on 5 March 1979 and the discovery of a series of short gamma-ray bursts, also determined to have a common source and to come from the same source direction as the giant flare, this new class of rare astrophysical phenomena was discovered. Somewhat later, these were named soft gamma repeaters (SGRs). In the subsequent Konus and Helicon experiments, studies of cosmic gamma-ray bursts and of soft gamma repeaters were continued, new SGR sources were found, and other giant SGR flares were also found. GRBs come from very distant cosmological sources, but SGR sources, analyzed in detail, have been localized in our Galaxy and in its satellite, the Large Magellanic Cloud (LMC). Recently and most notably, Konus measurements have been central in finding SGRs in the nearby galaxies M81 and M31, far outside our own Milky Way system. In the modern epoch of multi-wavelength studies of cosmic gamma-ray bursts, the joint Russian–American Konus–Wind experiment, which has already been operating for more than 15 years, provides important and often unique data regarding the various characteristics of these diverse types of transient gamma-ray emissions in the 10 keV to 10 MeV energy range.

R L Aptekar, S V Golenetskii, E P Mazets, V D Pal'shin, D D Frederiks
Ioffe Physical Technical Institute, Russian Academy of Sciences,
St. Petersburg, Russian Federation. E-mail: aptekar@mail.ioffe.ru

Uspekhi Fizicheskikh Nauk **180** (4) 420 – 424 (2010)
DOI: 10.3367/UFNr.0180.201004g.0420
Translated by R L Aptekar; edited by A M Semikhatov