The origin of deuterium

B. V. Vaĭner and Yu. A. Shchekinov

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"Diagnostics" of the early universe by means of light elements.—Deuterium in the solar system and in the galaxy.—Active processes during the pregalactic stage of the evolution of the universe and deuterium.—Galactic evolution and deuterium.

INTRODUCTION

About twenty years ago in the book of Ref. 1 it was noted that there is good agreement between the observed abundance of helium and the results of calculations using the hot model of the universe. But the authors of Ref. 1 pointed out that the problem can be finally solved only after obtaining more accurate information on the amount of helium being synthesized in the stars. At the present time there are no doubts concerning the cosmological origin of the main mass of this element. Moreover, obtaining more accurate information on the contribution of the stars to the production of helium opens up wide possibilities for utilizing its observed abundance in order to determine many parameters of the cosmological models (the degree of anisotropy, the number of different kinds of neutrinos, specific entropy, etc.).

The synthesis of chemical elements in the universe occurred in two stages. The first encompassed the initial phases of the expansion of several minutes duration and its result was the formation of the lightest elements: helium-4, helium-3, and deuterium.[2] The synthesis of the remaining elements of the periodic table began only a billion years later as a result of the birth and activity of the first stars.[3] This stage is continuing until the present day. The distribution of the elements is thus an imprint of the processes occurring at different stages of the evolution of the universe. Therefore, by studying the abundance of the chemical elements one could in principle reconstruct the entire history of the metagalaxy.[1)]

However, the situation is made complicated by the fact that at the second stage of the synthesis, when matter is condensed into stars and is subjected to reprocessing, the production of heavy elements is accompanied by a change in the abundance of the light ones (He^4, He^3, D). This distorts the information concerning the early stages of the evolution of the universe. What is the degree and what is the nature of these distortions? Can we using the observed abundances of helium and deuterium draw confident conclusions concerning the early universe? The indefiniteness in the data relevant to this problem is so great that within their framework varying opinions coexist, sometimes diametrically opposed to each other: either the cosmological abundances of helium and deuterium are altered only insignificantly by stellar evolution[4–6 2)], or the matter of the galaxies has been almost completely reprocessed by the stars so that the initial conditions have been "washed out"[7–8]; cf., also the discussion of the paper of Ref. 10.

In the present review we discuss practically all the mechanisms encountered in the literature and capable of altering to some extent the abundance of the products of cosmological nucleosynthesis. An analysis of their effectiveness enables us to obtain more definite estimates of the magnitude of these changes and, thereby, to utilize the observations of the light elements for choosing among cosmological models and determining their parameters.

1. "DIAGNOSTICS" OF THE EARLY UNIVERSE BY MEANS OF LIGHT ELEMENTS

At the present time the model which appears to be in best agreement with observations is the homogeneous isotropic hot model of the universe—the standard model.[2] This model is commonly characterized by the following parameters: the Hubble "constant" H_0, the average density of matter ρ_m or by the ratio of ρ_m to the critical density $\Omega_m = \rho_m/\rho_{cr}$, where $\rho_{cr} = 3H_0^2/8\pi G$, G is the gravitational constant; the specific entropy $s = n_\gamma/n_m$—the ratio of the number of quanta to the number of baryons. The results of calculations of the abundances of the light elements carried out within the framework of the standard model depend to some degree on these parameters, and therefore it is necessary to indicate the limits within which they are confined by the contemporary observations. In order to determine the Hubble "constant" several methods are available which lead at the present time to different results: for example, in accordance with Ref. 11, $H_0 = 50 \pm 25$ km/s·Mpc, while the authors of Ref. 12 give the value $H_0 = 80 \pm 25$ km/s·Mpc. At the same time there are available independent limits on the range of allowable values of the Hubble "constant". In particular, a lower bound of $H_0 > 40$ km/s·Mpc has been established using the ages of radioactive isotopes.[13] On the other hand, the presence within the galaxy of old globular clusters whose age is in any case not less than ten billion years makes it possible to set the upper limit as $H_0 \leqslant 100$ km/s·Mpc. These estimates depend only weakly on the parameter Ω.[3)] One can hope that the simultaneous observations of the x-ray and infrared radiations of galactic clusters planned for the near future will enable us to reduce significantly the indefiniteness in the measurements of H_0.[14,15] The same experiment will also provide the possibility of significantly increasing the accuracy

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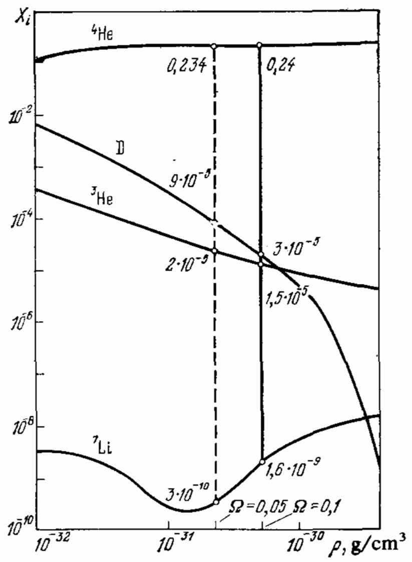

FIG. 1. Yield of light elements as a function of the average density of matter in the standard model of the universe.[23] The numbers denote values of mass concentrations for $\Omega_m = 0.1$ (solid line) and $\Omega_m = 0.05$ (dashed line).

of the value of the mean density of matter, the scatter in the determination of which at the present time attains two orders of magnitude. The average density estimated from the visible mass of the galaxies,[16] is $\rho_m > 5\cdot10^{-32}\ (H_0/50)^2$ g/cm^3. This lower limit for ρ_m can, apparently, be doubled taking into account the existing observations of the emission of x-rays from galactic clusters.[17]

Measurements of the retardation parameter[4)] provide the possibility of making an estimate of the total density of gravitating matter in the universe Ω. In accordance with Ref. 18 the upper limit is $\Omega \lesssim 1$. In the present situation the most accurate method of determining Ω_m is only by using the data on the nucleosynthesis of light elements.

Observations of relict radiation in the Rayleigh-Jeans region of the spectrum yield[19] $T = 2.72 \pm 0.08$ K, while for the background radiation integrated over all frequencies the value $T = 2.96^{+0.04}_{-0.06}$ K has been obtained.[20] Recent experiments[21] gave a value for the flux of microwave radiation lower by a factor of 1.5–2 than that obtained in Ref. 20. In future we shall assume $H_0 = 50$ km/s·Mpc, $\rho_{cr} = 4.6\times10^{-30} h_0^2$ g/cm^3 and $S = 5.34\cdot10^7\,(T/2.7)^3\,(\Omega_m h_0^2)^{-1}$, $h_0 = H_0/50$ and take into account all the uncertainties indicated above in comparing the results of calculations with observations.

The calculation of the abundances of the light elements carried out within the framework of the standard model yield mass concentrations of deuterium (X), helium-4 (Y) and helium-3 (X_3) which are close to the cosmic averages.[5,22,23] As can be seen from Fig. 1, the observed concentration of deuterium $X = (2-3)\cdot10^{-5}$ (cf., Sec. 2) can be obtained only if the matter density is $\rho_m \leqslant 4\cdot10^{-31}$ g/cm^3, which corresponds to $\Omega_m \leqslant 0.09$. The yield of helium $Y = 0.24$ at such a density taking into account subsequent stellar synthesis agrees with observations in the model with two sorts of neutrinos (ν_e and ν_μ). An increase in the number of kinds of neutrinos, as was shown for the first time by Shvartsman,[24] leads to an increase in the abundance of helium. The method proposed in Ref. 24 for the determination of the change in the yield of helium is cosmological nucleosynthesis depending on the number of kinds of different ultrarelativistic particles is being widely used for obtaining different kinds of limitations on the numbers of their types, their masses, their lifetimes, etc. (cf., for example, Refs. 25, 26), frequently regrettably without citing Ref. 24.

At present one can consider it as being established that there exists a third type of neutrino (ν_τ). The addition of each new sort of relativistic particle leads to an increase in the rate of expansion of the universe, as a result of which reactions involving the weak interaction which establish the "chemical" equilibrium between neutrons and protons, are "switched off" earlier at a higher temperature. The corresponding change in the abundance of helium is given by

$$\Delta Y = \frac{\Delta (n/p)_0}{(n/p)_0\,[1+(n/p)_0]}\,Y_0,$$

where Y_0 is the abundance of He^4 in the model with two kinds of neutrinos, $(n/p)_0$ is the ratio of the concentrations of neutrinos and protons at the moment of "quenching" (switching off of reactions). Since $(n/p)_0 = \exp(-\Delta mc^2/T_0)$ and $\Delta mc^2 = 1.28$ MeV, while the temperature T_0 is proportional to $[(11/4) + (7/8)n_\nu]^{1/6}$ [27] it is not difficult to make an estimate of ΔY: $\Delta Y = 7\cdot10^{-3}$ for $n_\nu = 3$[28,29] and $\Delta Y = 2\cdot10^{-2}$ for $n_\nu = 6$.[30] The dependence of the yield of helium on the number of kinds of neutrinos is shown in Fig. 2.

Here it should be noted that the indefiniteness in the measurements of the neutron decay constant ($\tau_n = 918 \pm 14$ s) gives rise to $\Delta Y = 10^{-3}$, which is entirely insignificant. Variations of T_{rel} from 2.7 K to 2.9 K lead to a change of S by a factor of 1.25 thereby decreasing the yield of He^4 by $\Delta Y = 0.002$ in a model with two kinds of neutrinos and by $\Delta Y = 0.003$ in a model with six kinds of neutrinos.

Comparing the results of calculations of the yield of helium-4 in the standard model with different values of the parameters (T_{rel} and n_ν) with observations, one can indicate the allowable range for the density of matter. An analysis of the HII regions in irregular galaxies carried out by Peimbert yields the abundance of He^4 as $Y = 0.225 \pm 0.015$. Castelani who studied the distribution of helium in globular clusters gives the value $Y = 0.23 \pm 0.01$ (according to Ref. 31). In-

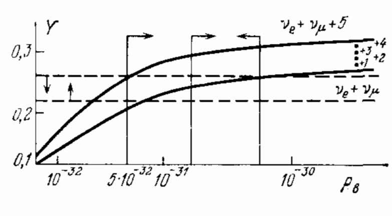

FIG. 2. The abundance of He^4 as a function of the average density of matter in models with different numbers of kinds of neutrinos.[30] Horizontal lines are limits on the abundance of helium imposed by observations, vertical lines are limits on the density of matter: the middle one in the case of $H_0 = 75$ km/s Mpc, the left-hand one—for $H_0 = 50$ km/s Mpc.

TABLE I.

$\bar{\rho}$, g/cm^3	$7\cdot10^{-31}$	$7\cdot10^{-31}$	$1{,}27\cdot10^{-30}$	$1{,}27\cdot10^{-30}$	$4\cdot10^{-30}$	$4\cdot10^{-30}$
$\frac{\rho_1-\bar{\rho}}{\bar{\rho}}$	$1{,}4\cdot10^2$	10^3	$1{,}4\cdot10^2$	$9{,}9\cdot10^2$	$9\cdot10^3$	9,9
α_1	$5\cdot10^{-3}$	$9\cdot10^{-3}$	$5\cdot10^{-3}$	10^{-3}	10^{-4}	10^{-2}
$\bar{X}$	$2{,}7\cdot10^{-5}$	$5{,}8\cdot10^{-5}$	$1{,}5\cdot10^{-5}$	$5{,}5\cdot10^{-5}$	$3{,}6\cdot10^{-6}$	$1{,}4\cdot10^{-5}$
$\bar{Y}$	0,272	0,277	0,277	0,300	0,330	0,298

α_1—fraction of the volume occupied by regions of high density; ρ_1 is the value of the density in these regions.

vestigation of the helium content in objects with a low concentration of metals indicates a restricted range of abundances of He^4: $Y = 0.22 - 0.26$.[32] Recent observations of the distribution of helium in 15 globular clusters yield an average value of $Y = 0.23 \pm 0.02$.[33] The low content of metals in the objects enumerated above enables one to consider that the quantity of He^4 in them differs but little from the pregalactic value. Then it is easy to show that $\rho_m = (5-23)\cdot10^{-32}$ g/cm^3 (cf., Fig. 1), i.e., $\Omega_m \ll 1$.

On the other hand, estimates of the virial masses of galactic clusters[34] yield a high density of matter ($\Omega \approx 0.3 - 1$). This gives rise to difficulties in explaining the observed abundances of helium and deuterium, if the hidden mass is due to the usual baryon matter (cf., Fig. 1). Of course, the hidden mass may be in the form of neutrinos with a rest mass different from zero ($m_\nu \approx 10$–30 eV) or in the form of other particles that are difficult to observe. Then this contradiction is removed. It should be noted that experiments on the determination of the neutrino rest mass carried out until the present time in different laboratories give contradictory results.[35,36]

We shall briefly consider a number of hypotheses advanced recently to solve the problem of the origin of deuterium in cosmological models with a high density of matter $\Omega_m \sim 1$. The required abundance D ($X \approx 5\cdot10^{-5}$) can be obtained in such models in the presence of developed entropy perturbations,[37–39] shift perturbations,[40] evaporation of primary black holes,[41,42] nonzero lepton numbers.[43,44] Indeed, in the case of a nonuniform distribution of matter the average concentration of the ith element can be calculated quite simply, viz.

$$\bar{X}_i = \frac{\int X_i(r)\,\rho_B(r)\,dr}{\int \rho_B(r)\,dr} = \frac{\int X_i(\rho_B)\,\rho_B f(\rho_B)\,d\rho_B}{\int \rho_B f(\rho_B)\,d\rho_B}.$$

If a high average density of baryons

$$\bar{\rho}_B = \frac{1}{V}\int \rho_B(r)\,dr$$

is attained as a result of the presence of islands of high density in a sea of matter of low density, the required abundance of deuterium can be obtained, as can be seen from Table I, only for a very large amplitude of entropy perturbations.[39,46] In Ref. 45 a continuous lognormal distribution of inhomogeneities over space is considered, i.e.,

$$f(\rho_B) = (2\pi\sigma^2)^{-1/2}\rho_B^{-1}\exp\left[-\frac{(\lg\rho_B-\mu)^2}{2\sigma^2}\right].$$

It is natural that also in this case in order to obtain the observed concentration of deuterium for $\Omega_m \sim 1$ very large deviations from the mean density ($\sigma \approx 2$) are required. Although the yield of helium depends only weakly on Ω_m, for such amplitudes of entropy perturbations it attains a value of $Y = 0.3 - 0.32$ which certainly contradicts observations since in the process of the evolution of the galaxy its abundance increases by $\Delta Y = 0.03 - 0.06$,[6] while the observed value lies within the limits $Y = 0.21 - 0.32$.[5] Similar difficulties arise in the model with shift perturbations.[40] In the grand unification theories the observed specific entropy can be expressed only in terms of the fundamental constants and the mass of the X-boson, and therefore some authors express doubt concerning the existence of entropy perturbation.[47,48]

In Ref. 39 an investigation was made of the effect of adiabatic fluctuations on the yield of light elements. It turned out that a significant increase in the abundance of deuterium in the case when $\Omega \sim 1$ can be attained only if the perturbations have amplitudes given by $|\delta T/T| \approx 0.9 - 0.99$. This calculation was repeated in a recent paper[49] with the same result. However, such perturbations are "forbidden," since, according to Ref. 50 the concentration of black holes with masses 10–$10^5 M_\odot$ formed from them would exceed all allowable limits.

The observed abundances of helium and deuterium limit the values of electron and muon lepton numbers to a narrow range of values (Fig. 3). It is impossible that the universe would specifically "select" these numbers in order to obtain the required concentrations of light elements. It is also clear that in the present theories of elementary particles in which a violation of the law of conservation of baryon charge takes place the lepton charge is also not conserved (for greater details cf., Refs. 27, 210).

The required abundance of deuterium can be obtained in the breaking up of He^4 nuclei by energetic neutrons evaporated from primary black holes.[41,42,51] In order to obtain the pregalactic abundance of deuterium $X = 5\cdot10^{-5}$ for

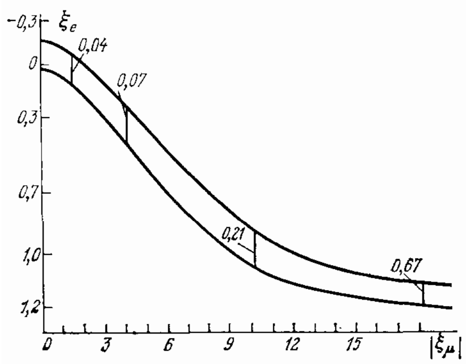

FIG. 3. The range of values of electronic ξ_e and effective muonic ξ_μ chemical potentials in which the yield of D, He^4 corresponds to present-day observations.[44] The numbers denote the value of Ω_m; $\xi_e = \mu_e/kT$; ξ'_μ is determined from the relation $\rho c^2 = T_\nu^4(1 + \frac{7}{2} + \frac{15}{4}\pi^{-2}\xi'^2_\mu + \frac{15}{8}\pi^{-4}\xi'^4_\mu)$.

$\Omega_m = 1$ one needs a density of primary black holes given by $\rho_{b.h}/\rho_m = 10^{-8}$. Indeed in Ref. 42 a calculation was made of the nucleosynthesis of light elements in the hot model of the universe and a dependence was obtained of the yield of D, He^3, H^4 on the parameters of the mass spectrum of primary black holes. In particular, the resultant concentration of deuterium for $T < T_0$ is

$$X = Y\left[1 - \exp\left(-\int_{T_0}^{T} \Lambda \frac{dt}{dT} dT\right)\right],$$

where $\Lambda \approx 8\Omega_{b.h} T^{8/3}$ is the rate of helium breaking up, $T_0 \approx 10^8$ K, and $\Omega_{b.h} \propto \rho_{b.h}/\rho_m$. Setting $Y = 0.26$ for $T = 10^5$K we shall obtain $X = 5\cdot 10^{-5}$, if $\rho_{b.h}/\rho_m = 10^{-8}$.

It is of interest to note a new direction of investigations associated with the breaking up of He^4 by antiprotons, in particular, also for the production of deuterium.[52,53] The increase in the mass concentration of this element has a result of the aforementioned processes will be given by

$$\Delta X = \frac{1}{2}\begin{cases} Y(f_D + f_n)R & 10^3 \leqslant t \leqslant t_D \\ Y f_D R & t > t_D, \end{cases}$$

where f_n and f_D are the average numbers of neutrons and D nuclei formed in the process of annihilation, $R = n_{\bar{p}}/n_p$ is the relative density of the antiparticles, $t_D = 4.5\cdot 10^6 \Omega^{2/3}$ s is the instant of time up to which the freed neutrons can still be captured by protons and form D nuclei. Since ΔX is certainly less than 10^{-4} it becomes possible to obtain strong restrictions on the content of antimatter in the universe, and also to narrow down the class of allowable models of the early stages of its evolution associated with the grand unification theories.[53]

On the other hand, at present astrophysicists devote considerable attention to the investigation of cosmological models with differ from the standard model.[54–60] In these models assumptions are made concerning either an anisotropic inhomogeneous distribution of matter, or a low specific entropy at the early stages of evolution of the universe. In the latter case attempts are made to explain the observed value of the energy density of the relict radiation (and its spectrum) by the emission of energy in the evolution of "stellar ancestors." The authors of these models succeed in attaining their objective only under very specific assumptions concerning the composition of matter (for example, a large amount of dust). But the yield of light elements in all these models differs to some degree from the observed values, and therefore hopes are expressed that the processes of evolution in the galaxy will strongly alter the concentration of light elements, bringing them up to the observed values. In this connection the question becomes particularly sharply posed concerning the variation of the abundances of the light elements in the course of the existence of the galaxy and, consequently, concerning the possibility of using data on the chemical composition of matter of the galaxy in order to select among cosmological models. It is also important to estimate the contribution to the production of light elements of different hypothetical processes occurring in the case of red shifts $z > 300$.[61,62 5)]

a) Helium-4. Observations of He^4 in different objects of our galaxy, and also in some other galaxies, yield values of the mass concentration $Y = 0.21 - 0.32$.[5,6 6)] An analysis of all the available observations enabled Reeves[4] to conclude that the average content of helium in the galaxy is $Y = 0.29 \pm 0.04$. What was then the abundance of helium at the stage preceeding the formation of galaxies? Recently Stecker[63] made an attempt to answer this question. The idea of his work consisted of the following. Since in the process of stellar evolution the abundance of helium increases, an upper limit can be placed on its yield in cosmological nucleosynthesis using the smallest of the values of Y observed in different objects. For Y_{min} he used the average value of the abundance of helium observed in blue and irregular galaxies: $Y_{min} = 0.228$. However, the absence of sufficiently reliable knowledge of the physical conditions in these objects (for example the characteristics of the ionizing radiation, the density of dust particles, etc.) makes the estimate of Y_{min} quite indefinite (for greater details cf., Ref. 6). Moreover, among the old stars of our galaxy there are stars within the atmospheres of which one observes $Y = 0.17 - 0.21$. Such a low value of Y is apparently due to the differential diffusion of elements in the atmospheres of these stars.

Evidently, an increase in the average abundance of helium in the galaxy as a result of its synthesis in stars is proportional to the content of heavy elements. The usual assumption is[6,64] $\Delta Y = (1 - 3)Z$, i.e., $\Delta Y = (2 - 6)\cdot 10^{-2}$. Therefore one can require from the cosmological models that the yield of helium should be confined to the range $Y = 0.20 - 0.25$. In the standard model the abundance of He^4 depends only weakly on the density of matter (Fig. 1). The indicated range of Y corresponds to densities of $\rho_m = 4\cdot 10^{-32} - 1.27\cdot 10^{-30}$ g/cm^3. This range of values of ρ_m is entirely contained within the previously mentioned lower bound on Ω_m and the upper bound on Ω.[7)] Such a great indefiniteness in ρ_m leads to considerable arbitrariness in the choice of parameters for the theories of the origin of the large-scale structure of the universe.

We call attention to some other possibilities of an independent determination of Ω. In Ref. 65 an attempt was made to discover protogalaxies directly. Based on theoretical cal-

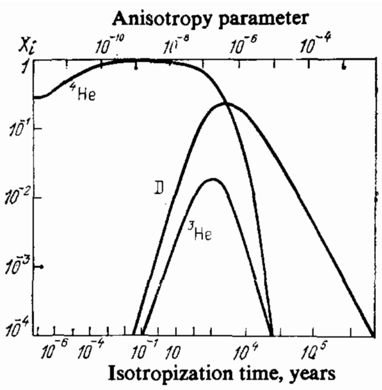

FIG. 4. Yield of light elements as a function of the anisotropy parameter (upper scale) and the instant of isotropisation (lower scale).[74]

culations indicating an intense emission of energy and, consequently, an increased luminosity of protogalaxies, the authors searched for radiation from these objects with the aid of a special highly sensitive photometer in the wave length range of $\lambda = 6200$–8900 Å. As a result with a reliability of 90% no radiating objects were recorded in the investigated area of the sky free from visible sources. The upper limit on the flux in the range of wavelengths indicated above is $F < 38\cdot 10^{-29}$ erg·cm^{-2} s^{-1} Hz^{-1}. Therefore, in Ref. 65 a conclusion is reached that the moment of the formation of structure in the universe is $z_s > 9$. On the other hand, in the standard model with $\Omega < 1$ the growth of perturbations continues up to $z = 0.4/\Omega^2$. Then from the result of Ref. 65 it follows that $\Omega < 0.04$. However, this conclusion cannot be regarded as convincing. The point is that the estimates in Ref. 65 of the expected radiation flux in the range under investigation are made on the basis of a quite specific model of the protogalaxy which might not correspond to reality.[66] But in reality, as is shown in Refs. 67–70, in order to explain the observed structure in the universe sufficiently high values of Ω are needed. Indeed, for $\Omega = 0.03$ it would be necessary for the magnitude of the perturbations of the density of matter at the time of recombination of hydrogen to be given by $\delta\rho/\rho \sim 10^{-2}$, and this is certainly in contradiction with the available observations of the isotropy of relict radiation. The upper bound on the amplitude of the fluctuations[70,71] $\delta T/T \lesssim 8\cdot 10^{-5}$ established by observation requires $\Omega_m \gg 0.03$.[68,69] This requirement is somewhat relaxed taking into account the finite neutrino mass.[72]

Apparently, in order to solve the problem of the determination of the density of matter within the framework of the standard model it is necessary to bring in data on nucleosynthesis also of other light elements (D, He^3).

In the hot and "warm" models of the universe[54] with a low value of the initial specific entropy $S \ll 10^7$, the synthesis of the elements occurs at significantly higher densities of matter than in the standard model, and therefore the yield of He^4 significantly exceeds the limit ($Y_{max} = 0.25$) established by observation. This increase can be compensated only by a special choice of the magnitude of the lepton charge.[73]

In anisotropic homogeneous cosmological models the yield of He^4 agrees with observations for a definite choice of the anisotropic parameter[74,75] (Fig. 4). But in inhomogeneous anisotropic models it is possible to obtain the required abundance of He^4 over a wide range of parameters.[76] Thus, the existence of a wide class of cosmological models within which the yield of He^4 on the whole agrees with present-day observations and also the weak dependence of the content of helium on the parameter Ω_m in the standard model enable one to conclude that by itself He^4 cannot be a sufficiently critical test for the choice of an adequate scenario for the evolution of the universe.

b) Lithium. According to the calculations of Wagoner,[23] in order to obtain the deuterium abundance of $X \gg 3\cdot 10^{-5}$ it is necessary to have $\Omega_m \ll 0.1$. In this case the atom yield of the lithium isotopes will be: $Li^7/H \ll 2.3\cdot 10^{-10}$, $Li^6/H < 10^{-12}$. At the same time according to observations in different regions of the galaxy[4,77] we have $Li^7/H = (3-10)\cdot 10^{-10}$ and $Li^7/Li^6 = 12 - 15$.[5] Since lithium as well as deuterium is burned up in hot stars it is evident that the origin of Li and its isotopic composition cannot be completely explained by nucleosynthesis during the early stages of the expansion of the universe.

One of the sources of obtaining this element is the breakdown of nuclei of heavier elements in interstellar space by galactic cosmic rays.[78,79] However, as was demonstrated in Ref. 80, this mechanism can explain the observed abundances only of Li^6, Be^9, B^{10}. A small contribution to the content of Li^7 in the interstellar medium could be made by the red giants the atmospheres of many of which are enriched in lithium.[81,82] The observed abundance of Li^7 can also be obtained in the process of cosmological nucleosynthesis if one assumes a nonzero lepton charge.[44] At the present time the most suitable process for the generation of Li^7 appears to be its synthesis in shock waves from supernovae. According to the calculations of Ref. 83 the factor of the enrichment of gas with lithium compared to its average abundance can attain values of 10^5, if the ions in the shock wave are heated to $T \approx 10^{11}$ K, which corresponds to energy generation accompanying the explosion of a supernova of $\approx 10^{53}$ erg. Under more realistic assumptions, taking into account the energy of explosion of a supernova to be $= 10^{51}$ erg and considering that 10–20% of the interstellar gas passed through a supernova stage and using the results of Ref. 83 one can obtain the content of lithium in the interstellar medium $Li^7/H \approx 10^{-9}$. In this case the ratio of the concentrations of the lithium isotopes turns out to be excessively high $Li^7/Li^6 > 10^3$. Apparently, the solution of the problem of the isotopic composition Li^7/Li^6 should be sought along the path of bringing together different mechanisms. A review of the situation associated with the origin of Li, Be, B, is given in Refs. 84, 85.

It should be noted that the uncertainties associated with the errors in the observations of lithium, the evolution of the abundance of lithium in stars, the parameters of the cosmic ray spectrum, etc. at present are very great (factor ~ 5), and therefore the use of the observed distribution of lithium as a test of cosmological models does not appear to be possible for the time being.

c) Deuterium. In contrast to helium, deuterium is considerably more sensitive to the conditions in the early universe. In the standard model for a density of matter $\rho_m = 3\cdot 10^{-31}$ g/cm^3 the yield of D is $X = 6\cdot 10^{-5}$, while for $\rho_m = 4\cdot 10^{-39}$ g/cm^3 it is $X = 10^{-8}$ (cf., Fig. 1).[23] Naturally, in the warm models, where the specific entropy is $S \lessdot 10^7$ and, consequently, the synthesis of elements occurs at higher density of matter, too small an amount of it is produced (D rapidly burns up to Ae^4).[7] The point is that deuterium is destroyed in the binary reactions of the type $D + p \rightarrow He^3 + \gamma$ at a temperature of $10^7 < T < 10^9$ K and photodisintegration at $T > 10^9$ K. Therefore the rate of thermonuclear burnup of it into heavy elements, $X^{-1}\, dX/dt$ is proportional to the density of matter ρ_m, while the rate of synthesis in the reaction $p + n \rightarrow D + \gamma$ decreases exponentially as a result of neutron decay. The resulting abundance of this isotope is determined by the small fraction of nuclei "surviving" as a result of nuclear burnup, with this fraction being the lower, the higher is the value of ρ_m. In homogeneous anisotropic models of the universe it is in general impossible to obtain simultaneous agreement with observations of the abundances of He^4 and D (cf., Fig. 4). In inhomogeneous anisotropic models calculation leads to a large excess of deuterium (by almost three orders of magnitude).[76]

Apparently deuterium is a unique stumbling block, any attempt to depart from the standard model with $\Omega_m \lesssim 0.1$ leads to a noticeable difference between the predicted abundance of D and the observed one. Is the further evolution of the galaxy (or the assumed active processes in the pregalactic stage) able to alter significantly the content of deuterium? Before going on to the analysis of the latter problem we shall briefly discuss the available observations on the distribution of D.

2. DEUTERIUM IN THE SOLAR SYSTEM AND IN THE GALAXY

Measurements of the deuterium content in the solar system lead to the following results: in ocean water in terms of the concentration of HDO molecules[8] $d = D/H = 1.5\cdot 10^{-4}$,[86] in meteorites $d = (1.3 - 2)\cdot 10^{-4}$,[87,88] and on Jupiter in terms of the HD and CH_3D molecules $d = (3 - 8)\ 10^{-5}$.[89,90] Deuterium was not observed on the sun due to its being burned up in the reaction $p + D \rightarrow He^3 + \gamma$. Since in the upper layers of the sun He^3 is not burned up, then based on the abundance of this isotope in the solar wind and in the solar corona an upper limit $d_{ps} \leqslant 5\cdot 10^{-5}$ is obtained in the protosolar gas.[9] Deuterium nuclei with an energy of ~ 10 MeV/nucleon are recorded during solar flares. Their density $d = (8 \pm 2)\cdot 10^{-5}$ is explained by the effects of the interaction of high energy particles accelerated in the chromosphere of the sun,[91] and therefore is not connected with the abundance of deuterium in the protosolar gas.

The question arises as to what is the relation between the currently observed abundance of deuterium in the solar system and the value of d in the interstellar medium from which the protosolar cloud separated out five billion years ago.

In order to determine the abundance of deuterium in the protosolar gas it is necessary to take into account the effects of chemical fractionation which arise due to the fact that the binding energy of deuterated molecules is greater than that of molecules containing the main hydrogen isotope. Therefore, at low temperatures it is energetically more favorable for the mixture to become enriched in deuterated molecules. For example, heavy water is formed in the reaction

$$HD + H_2O \rightleftharpoons HDO + H_2,$$

in which the water is in contact with a hydrogen reservoir. Then, under the conditions of chemical and thermodynamic equilibrium, d (in water) $= K(T) d$ (in hydrogen). The reaction constant $K(T)$ increases exponentially as the temperature is reduced (as tabulated in Ref. 93). A detailed analysis of the chemical processes occurring in the protosolar nebula leads Geiss and Reeves[94] to the conclusion that $d_{ps} = (2 - 3)\cdot 10^{-5}$. A closely similar estimate $d_{ps} = 2\cdot 10^{-5}$ was obtained by Geiss and Bochsler.[95]

Atomic deuterium was observed in interstellar medium using the lines $L_\beta - L_\zeta$ in the absorption spectra of rapidly moving stars.[96] The authors estimate its abundance as $d = 1.5\cdot 10^{-5}$. The same value is also given in later papers.[97,98] The stars $\delta, \varepsilon, \iota$ Ori, ξ Pup, γ Cas, etc., were used as sources of radiation (cf., caption to Fig. 5). The density of deuterium atoms along the line of sight is $N_D \approx 10^{15}$ cm^{-2}, while the line of sight density of neutral hydrogen is $N_H \approx 10^{20}$ cm^{-2} (in the direction of ι Ori), which yields $D/H = 7.5\cdot 10^{-6} - 1.5\cdot 10^{-5}$.[98] It should be noted that recently in Ref. 98 the earlier results on the determination of d in the direction of ε Per have been reexamined and the value of $d = 5\cdot 10^{-6}$ has been obtained (instead of $1.5\cdot 10^{-5}$). However, four-hour variations in the abundance indicate that the observations refer to the small neighborhood of a bright star and do not reflect the actual abundance of deuterium in the interstellar gas. From observations of the absorption of ultraviolet radiation of stars by HD molecules values of d are obtained of the same order of magnitude.[100,101] In particular, in the molecular cloud ξ Oph one obtains $2\cdot 10^{-6} < d < 2\cdot 10^{-4}$ taking chemical fractionation into account.

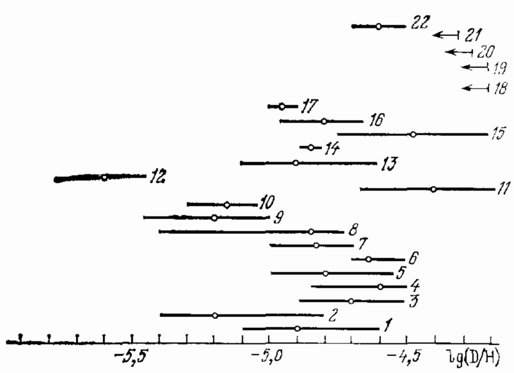

FIG. 5. Summary of observations of deuterium and deuterated molecules in the galaxy. 1–13—observations of the Lyman lines of atomic deuterium in absorption in the direction towards nearby stars (1–5 from Refs. 98, 209; 6–7 from Ref. 97; 8, 10 from Refs. 6, 98; 11–12 from Ref. 206; 13—from Ref. 207 respectively); 14–16—observations of the absorption of ultraviolet radiation of stars by HD molecules[208]; 17—observations of DCN in the Orion nebula[102,103]; 18–20—upper limit according to observations using the 91.6 cm line[106–109]; 21—upper limit for the protosolar gas; 22—determination of the abundance of deuterium in the protosolar gas taking chemical fractionation into account.[94,95]

All the results mentioned above refer to a local region of dimensions up to 1 kpc. Observations of deuterium in radio lines make it possible to determine its abundance on a sclae comparable with the dimensions of the galaxy. In the Orion nebula according to the observation of Ref. 102 at frequencies of 72 and 145 GHz in DCN the value of DCN/HCN $= 6\cdot10^{-3}$ was obtained. In order to determine D/H in this nebula it is necessary to consider chemical reactions for the production and disintegration of deuterated molecules:

$$\mathrm{HD} + \mathrm{HCN} \rightleftarrows \mathrm{H_2} + \mathrm{DCN},$$
$$\mathrm{D} + \mathrm{HCN} \rightleftarrows \mathrm{DCN} + \mathrm{H}.$$

Due to the difference in the binding energies of HCN and DCN we shall have[103]

$$\frac{\mathrm{DCN}}{\mathrm{HCN}} \approx 2\frac{\mathrm{D}}{\mathrm{H}}\, e^{456/T}.$$

Then, assuming that molecules are formed in cold clouds[10)] with $T = 80 \pm 10$ K we obtain[105] $d = (1 - 1.5)\cdot10^{-5}$.

A considerable fraction of deuterium exists in the interstellar medium in the atomic state, and therefore extensive information on the distribution of this element in the galaxy free from effects of chemical fractionation could be obtained from observations of the absorption of the hyperfine structure line of the ground state ($\lambda = 91.6$ cm). This possibility was pointed out for the first time by I. S. Shklovskiĭ in 1948. As a result of such measurements in the direction of the galactic center the upper limit $d < 3.5\times10^{-4}$ was obtained,[106,107] and in the direction of the radio source Cas A the value of $d < 7\cdot10^{-5}$ [108] was obtained. A more restrictive limitation on the abundance of deuterium in the direction of the galactic center was obtained in a recent paper[109] ($d < 5.8\cdot10^{-5}$). As can be seen from the limits quoted above, in order to obtain a reliable determination of the abundance of deuterium using the 91.6 cm line it is necessary to increase the sensitivity of the radiotelescopes by approximately fivefold. A summary of the observations available at present of atomic deuterium and deuterated molecules is given in Fig. 5.

All the results quoted above show that in the interstellar medium the average value at the present time is $d = (1 - 3)\cdot10^{-5}$ and was approximately the same about five billion years ago in the protosolar gas (cf., the foregoing discussion and Refs. 94, 95). Does this value reflect the cosmological abundance of deuterium or is it the result of transformation of the primary matter in active processes at stages of the evolution of the universe and the galaxy which preceeded the formation of the solar system?

Reference 9 presents the following arguments in support of a significant decrease in the abundance of deuterium (by a factor of approximately 40) in the course of the existence of the galaxy: observations of the distribution of D in the giant planets of the solar system yield $d = (3 - 8)\cdot10^{-5}$ which is higher by a factor of 2–3 than in the present interstellar medium. Therefore, during 5 billion years (the age of the solar system) the abundance of deuterium decreased by a factor of 2–3, while during 20 billion years (the age of the galaxy adopted in Ref. 9) the destruction factor amounts to $\sim 2.5^4 \approx 40$. However, the arguments presented in that paper seem to be inconclusive. Firstly, as has been pointed out already, the formation itself of the planets of the solar system can be accompanied by considerable chemical fractionation and therefore the observations in the giant planets, which are conducted using the molecular lines of HD and CH_3D[89,90] yield overestimates of d_{ps}.[110] The upper limit $d_{ps} < 5\cdot10^{-5}$ obtained using He^3 corresponds to the results of Refs. 94, 95 $d_{ps} = (2 - 3)\cdot10^{-5}$ which are only by a factor of 3/2 greater than the value in the interstellar medium. Secondly, the rate of destruction of deuterium is determined by the fraction of the interstellar gas that has passed through the stage of thermonuclear combustion in stars, and does not depend on the abundance of D in the interstellar medium (cf., below). Thirdly, the age of the galaxy determined from the globular clusters amounts to 12–16 billion years.[111] Taking all these factors into account the degree of destruction of deuterium does not exceed five. Undoubtedly, this result requires further improvement. Recently a number of attempts has been made to determine the ages of the oldest objects of our galaxy—the globular clusters. Unfortunately, in practice it has not been found possible to narrow down the range of allowable values. According to the data of Ref. 112 we have $t = (16 - 17)\cdot10^9$ a, the authors of Ref. 113 propose a wider range of ages $t = (13 - 20)\cdot10^9$ a, while Ref. 114 gives $t = (8 - 19)\cdot10^9$ a with the most probable value of $15\cdot10^9$ a. At the same time, while we know the abundance of D in the giant planets of the solar system relatively accurately, the indefiniteness in the values of d_i in the interstellar medium is very great. And it is specifically the ratio d_{ps}/d_1 that gives the degree being sought of the destruction of deuterium during the time of the existence of the solar system, i.e., during $5\cdot10^9$ a. Therefore, in Ref. 115 an assertion is made that the degree of destruction of deuterium does not exceed five, while Ref. 32 asserts that $d_{ps}/d_1 = 2 - 8$. It is to be hoped that the placing in orbit of a space telescope with a mirror diameter of 2.4 m will make it possible to increase significantly the accuracy of the observations of atomic deuterium in the interstellar medium, while the development of adequate models of the chemical evolution of the galaxy which would permit the calculation of the abundance of different elements and their radial gradient (cf., for example, Ref. 116), will facilitate a significant increase in the accuracy of the value of the pregalactic abundance of deuterium.

Recent measurements of the positive gradient in the distribution of D in the galaxy[117] (Fig. 6) which indicate according to Refs. 118, 119, a pregalactic origin of deuterium[11)] are also very significant for the elucidation of the degree of correspondence between the original and present abundances of this element. In order to obtain the distribution of $d = $ D/H from the ratios DCN/$HC^{13}N$ and DCO^+/HCO^{18+}, measured by Penzias, it is necessary to take into account the effects of chemical fractionation, which can produce significant indefiniteness (cf., for example, Ref. 121).

In Ref. 122 it is shown that the effects of chemical fractionation of deuterium themselves depend on the position of some particular cloud in the galaxy. This is associated with the fact that the formation of molecules in the interstellar gas, including the deuterated ones, is brought about primarily by the gas-phase ion-molecular reactions. As a result, the

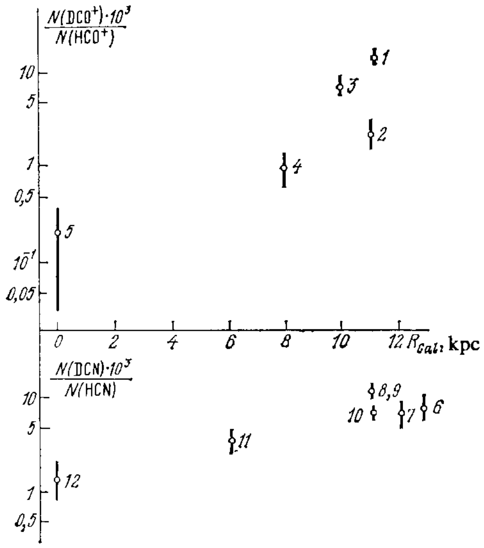

FIG. 6. Observations on the distribution of concentrations of deuterated molecules along the galactic radius.[117] 1—NGC 2264, 2—Ori A, 3—DR21, 4—M17A, 5—Sgr B, 6—NGC 7538, 7—W3 (OH), 8—OriA, 9—0.2′, 10—0.4′, 11—W33, 12—Sgr A. Only the statistical error is shown.

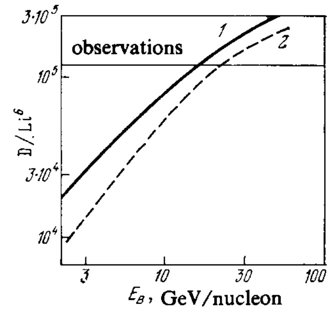

FIG. 7. Ratio of the D and Li^6 contents[133] as a function of the characteristic energy of the particles in the spectrum. The spectrum is chosen in the form $F(E) \propto (E+E_B)^{-2.5}$; 1—initial ratio D/Li^6, 2—D/Li^6 taking into account the subsequent destruction of D.

enrichment of molecules by deuterium is more effective in those regions in which there is a higher relative concentration of molecular ions. In turn, their concentration is limited by the reactions of dissociative recombination and therefore depends on the efficiency of sources of free electrons. Since the main source of electrons in molecular clouds are atoms of elements with low ionization potentials (Fe, Mg, etc.), then an increase in their content leads to an increase in the frequency of processes of dissociative recombination and, consequently, to a decrease in the concentration of molecular ions. Therefore, the more heavy elements there are present in a gas, the weaker will be in it the effects of enrichment of molecules by deuterium. According to estimates of Ref. 122 the fraction of deuterated ions $HCO^+DCO^+/HCO^+ \propto (FZ)^{-1/3}$, where F is the flux of ionizing radiation, Z is the abundance of heavy elements in the gas. At the present time there exist convincing arguments in favor of the fact that both F and Z increase towards the center of the galaxy.[123–125] And this means that an appreciable contribution to the change in the concentration of deuterated molecules in the galaxy can be introduced by a change in the conditions of chemical fractionation. Here one should note the fact that the anomalously low value of DCO^+/HCO^+ in the source SgrB (cf., Fig. 6) compared with other regions may be associated specifically with the anomalously strong weakening of the effects of fractionation at the center of the galaxy.

The estimates quoted above indicate a weaker radial gradient of the distribution of deuterium in the galaxy, than is obtained from the observations of deuterated molecules. The observed growth in the relative concentrations of molecules containing deuterium by a factor of 15–30 from the center towards the periphery of the galaxy apparently corresponds to an increase in D/H by not more than tenfold.[12)] A decrease in the gradient of the distribution of deuterium indicates a decrease in the degree of alteration of the composition of the interstellar gas by the stars. However, it does not appear to be possible to calculate the degree of destruction of deuterium on the basis of the available data on the radio distribution of deuterated molecules. This is due to the insufficient number of objects that have been investigated. One might hope that the planned new measurements of the content of DCN in 13 molecular clouds[126] will enable us to give a more accurate estimate of the effects of chemical fractionation and the value of the gradient of D/H.

3. ACTIVE PROCESSES DURING THE PREGALACTIC STAGE OF EVOLUTION OF THE UNIVERSE AND DEUTERIUM

An insufficient abundance of deuterium obtained in the process of cosmological nucleosynthesis in the standard model of the universe with $\Omega_m > 0.1$ stimulated the investigation of different possibilities of the production of this element in a later period. At first glance, the simplest method of increasing the deuterium content consists in the breakup of He^4 nuclei, whose origin is supposed to be cosmological, by energetic particles arising in the course of evolution of massive pregalactic objects "prequasars".[61,62] However in collisions of energetic α-particles with He^4 nuclei of the surrounding gas such isotopes will be made as Li^6,Li^7 and, moreover, the production of π^0 mesons in reactions $p + p \to \pi^0 + \ldots$ will lead to the appearance of a large number of quanta with an energy of ~ 70 MeV. The ratio D/Li^6 depends very strongly on the energy of the particles bombarding the "background"[133] (Fig. 7). In order to obtain this ratio close to the observed value it is necessary for the average energy of the particles to satisfy $E_0 \gtrsim 30$ GeV/nucleon. As calculations have shown[61] the gamma radiation arising in this case can be diminished to the observed level only if such violent processes occur immediately after the instant of recombination, i.e., when $z \gtrsim 400\Omega^{-0.3} h_0^{-0.6}$.

In order to obtain the mass concentration of deuterium $x \approx 10^{-5}$ it is necessary to have an energy liberation of $q = 6\cdot 10^{18}$ erg/g. Such an amount of energy can be in principle obtained in the evolution of massive pregalactic objects, but, as the calculations of Wagoner have shown[134] a sufficiently large quantity of heavy elements is synthesized in supermassive objects. In the formation of the entire observed mass of iron from hydrogen the energy liberated amounts to only $q_{Fe} = 10^{16}$ erg/g. Therefore one might expect that the liberation of energy assumed by Epstein[61] will lead to an excess of heavy elements in comparison with observation. Although at present there are no detailed calculations of the synthesis of elements up to Fe in objects of mass $\sim 10^5 - 10^6 M_\odot$ the results of Ref. 135 for a supernova with $M = 10 M_\odot$ and $q = 5\cdot 10^{16}$ erg/g indicate a significant production of heavy elements (cf., also Refs. 136, 137). According to Ref. 138, massive stars ($M \gg 80 M_\odot$) with primordial chemical composition will in the course of their evolution eject matter composed of 60% of oxygen O^{16} and of 14% of silicon Si^{28}.

Therefore the yield of deuterium associated with the activity of "prequasars" must not at any rate exceed the value of $x \lesssim 10^{-7}$. The above arguments lead to making doubtful the possibility of the production of the observed abundance of D by energetic particles from "prequasars".

Sometimes as an argument in favor of pregalactic nucleosynthesis the presence is brought foreward of a noticeable abundance of metals ($Z \approx 10^{-4}$) in the oldest stars of the galaxy. But if the pregalactic matter did not contain heavy elements then, according to the calculations of Silk[139] (cf., also Ref. 140), the masses of the first stars were sufficiently large[13)] ($\sim 20 M_\odot$). Such stars evolve rapidly, during a time $t_* \approx 10^6$ a a large fraction of them is converted into supernovae and enriches the surrounding medium by heavy elements. Assuming that the duration of the process of formation of the first stars is $t = 10^8$ a (the Jeans time, corresponding to an initial density in the protogalaxy of $\rho = 10^{-24}$g/cm^3) and that the chemical composition of the matter of ejected shells is similar to the present composition in the case of SNII, one can obtain the mass concentration of heavy elements $Z \approx 10^{-4}$ if the fraction of the matter of the galaxy that has passed through the first generation supernovae is $f \approx 0.01$.

Assuming that the energy liberated in the formation of heavy elements is radiated with an efficiency of $\xi < 1$, the luminosity of a young galaxy can be estimated to be[142,143]

$$L = 4\cdot 10^{55} \xi \frac{\Delta Z}{\Delta t} \text{ erg/s}, \tag{3.1}$$

(where Δt is the time in years, ΔZ is the mass concentration of heavy elements). Assuming $\Delta t = 10^8$ a, $\Delta Z = 10^{-4}$, we obtain $L = 4\cdot 10^{43}$ erg/s, i.e., the formation of the required quantity of heavy elements by first generation stars does not even require an increase in the luminosity of the galaxy compared with the present value: $\sim 10^{44}$ erg/s.

Thus, the presence of heavy elements in the oldest stars of the galaxy can be explained without requiring the hypothesis of their pregalactic origin in "prequasars".[14)]

4. GALACTIC EVOLUTION AND DEUTERIUM

a) Nuclear synthesis in stars and the burnup of deuterium. A decrease in the abundance of deuterium is associated with its burning up in stars in the reaction $p + D \to He^3 + \gamma$. The competing weak-interaction reaction $p + p \to D + e^+ + \nu_e$ has a rate smaller by several orders of magnitude, and is therefore incapable of replenishing the burned-up deuterium. Even in the outer layers of the star where the temperature and the density are, respectively, only $T = 4\cdot 10^6$ K and $\rho = 5$ g/cm^3, the deuterium burns up during a characteristic time of $\tau = 10^4$ s. Therefore, if in the process of evolution the star loses mass, then the interstellar medium has added to it matter which practically does not contain deuterium.[15)] As a result of such a cycle of matter in the galaxy the concentration of deuterium in the interstellar medium decreases. Since deuterium has never been observed in stellar atmospheres, then the key to the solution of the problem of its pregalactic abundance should be sought only in the interstellar medium.

It is of interest to note that recently attempts were made to measure the abundance of D directly using the H_α line in the atmosphere of Canopus.[145] As should have been expected, only an upper limit $d < 5\cdot 10^{-7}$ was obtained.

If the fraction of the mass of the present interstellar gas that has passed through the stars is equal to f, then the observed abundance of deuterium in terms of the number of particles should amount to $(1-f)d_0$, where d_0 is its pregalactic abundance.

Thus, our problem reduces to estimating the value of f. A contribution to reprocessing of interstellar deuterium can be made only by stars with a mass exceeding a solar mass: $M > M_\odot$. Less massive stars evolve during a time greater than the age of the galaxy, and therefore do not take part in recycling matter.[111] Consequently, it suffices to restrict ourselves to stars with $M > M_\odot$. Let us turn to observations.

According to the data of Ref. 146 the rate of ejection of gas per unit volume of the galaxy by massive stars which are at the stage of burning helium[16)] amounts to $\dot\rho \approx 3\cdot 10^{-13} M_\odot$/a·pc^3. A closely similar value is provided by massive stars at the stage of burning hydrogen[17)]: $\dot\rho \approx 1.5\cdot 10^{-13} M_\odot$/a·pc^3 (cf., Refs. 146–149). According to Ref. 147, approximately the same amount of matter is introduced into interstellar space from planetary nebulas. These estimates are determined, as a rule, with an accuracy up to a factor of $\approx$2–3, which is related first of all to the indefiniteness in the rate of loss of mass by an individual star and to the indefiniteness in the spatial density of stars of this type. In particular, in our opinion, the rate of ejection of matter by planetary nebulas is hardly likely to exceed $\dot\rho_{PN} \approx 0.5\cdot 10^{-13} M_\odot$/a·pc^3, since a higher rate of loss of mass $\dot\rho_{PN}$ would lead to an excessive enrichment of the interstellar medium by helium. Indeed, according to the data Ref. 130 the mass concentration of He^4 in the shells of more than 80% of the investigated planetary nebulas exceeds $Y = 0.44$. Therefore the total rate of loss of matter by massive stars can be estimated to be $\dot\rho \approx (2-20)\cdot 10^{-13} M_\odot$/a·pc^3. Stars with masses close to the solar mass as a rule lose matter much less effectively: $\dot\rho \approx 10^{-15} - 10^{-16} M_\odot$/a·pc^3.[146] Assuming that all these stars are distributed uniformly over a disk of radius 15 kpc and with a thickness of 1 kpc, we shall obtain for the loss of mass by these stars in the galaxy $\dot M = 0.1 - 1\, M_\odot$/a.

The indefiniteness in estimating the rate of ejection of matter by double stars is even greater than in the case of single stars. According to the data of Ref. 150 the total loss of mass by double stars in the galaxy amounts to $\dot M_m = 1.8 M_\odot$/a. This estimate is made on the basis of measuring the increase in the period of the binary system SS Cyg and the corresponding rate of outflow of gas $1.8\cdot 10^{-7} M_\odot$/

a [151] and appears to be clearly an overestimate: such a high rate of loss of mass would lead to the formation around the binary system of a dense shell as a result of which the system would turn out to be invisible in the optical range[152,153] (cf., also the discussion in the paper of Ref. 150). According to the calculations of Refs. 152, 153, the actual losses of mass by binary systems of this type can attain values of only $\sim 10^{-2} M_\odot/a$.

It should be noted that estimates of the rate of ejection of matter by binary stars made using the data on the variation of the period are always overestimates since these variations can be associated apparently not with the ejection of the mass from the system but with the presence of a third component. Evidence of this, for example, are the nonmonotonic variations of the period[152], and also variations in the elements of the orbits of some binary stars.[154,155] Generally speaking, the main flow of mass in binary systems is due to a transfer of matter from one component to the other, rather than to ejection into the interstellar space. Evidence for the low rate of ejection by binary stars also comes from spectroscopic observations in the ultraviolet region. According to Refs. 156,157, massive stars ($M > 10 M_\odot$), which are components of binaries, as a rule lose less matter than similar single stars.[18)] But, as we have seen above, it is just the massive stars that give the principal contribution to supplying interstellar space with gas, and, therefore, if one takes into account, following Ref. 156, that of all the massive stars approximately 40% are components of binaries, one can estimate the rate of ejection of gas by them by the expression

$$\dot{M}_B \leqslant 0.025 - 0.25\ M_\odot/a .$$

Moreover, one should keep in mind that the matter lost by binary stars must contain an excess of helium. This is indicated both by theoretical calculations[159], and also by direct observations of the deficiency of hydrogen (from 0.5 to 0.025 compared with helium) in the surface layers of stars that are members of binaries.[160,161] Therefore the rate of ejection of matter by such binary systems should not exceed the value of $5\cdot 10^{-2} M_\odot/a$, in order not to increase noticeably the abundance of helium in the interstellar gas compared with observations.

More significant can be emission of matter from novae and supernovae. Incidentally in recent years a greater role is ascribed to supernovae in enriching the interstellar space by matter than was the case a few years ago. In 1969 Pottasch[146] estimated the rate of ejection by supernovae to be $10^{-2} M_\odot/a$ as a total over the galaxy, and according to the latest data this number should be increased at least by an order of magnitude. Indeed, according to Ref. 162, the maximum frequency of supernova explosions in the galaxy amounts to $1/27\ a^{-1}$, with the most probable value being $1/48\ a^{-1}$. Assuming for supernovae of the second kind the mass of ejected matter as $\sim 5 M_\odot$ [111,163], we obtain an estimate of the upper bound for the rate of ejection of matter as $\dot{M}_{SN} \lesssim 0.2 M_\odot/a$ with the most probable value of $\dot{M}_{SN} \approx 0.1 M_\odot/a$. The problem of ejection of matter from supernovae of the first kind is far from having been solved, but in recent years many authors are inclined to the opinion that these objects might eject into interstellar space the same amount of gas as do the supernovae of the second kind (Fig. 8). Evidence for this is the sufficiently large mass ($> 1 M_\odot$) of matter ejected by an individual supernova of the first kind,[111] and also their possible connection with the young population of spiral and irregular galaxies.[164]

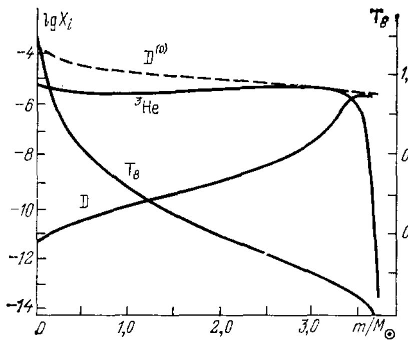

FIG. 8. The yield of D and He^3 and the dependence of the temperature on the mass contained within the given radius.[187] $T_8 = T/10^8$ K. The dashed line—without taking into account the further burning-up of D, the solid line—the actual concentration of D.

One can find restrictions on the rate of ejection of matter from supernovae based on comparing the chemical composition of the material ejected by them with the average cosmic chemical composition. If one assumes that the abundance of iron in the matter ejected by supernovae is the same as in cosmic rays, specifically greater by a factor of 5–20 than the cosmic average,[165] then $\dot{M}_{SN} \leqslant 0.1\ M_\odot/a$.[166] A value close to this can be obtained if one assumes according to the calculations of Refs. 167, 168 (cf., also Ref. 136), that in a supernova explosion matter is ejected in which the abundance of iron exceeds the solar abundance by a factor of 15. Evidence for this is also provided by direct observations of SN *I*.[169,170] We note, however, that the x-ray spectrum of the shell of Tycho's supernova (of the first kind) does not exhibit such a significant excess of iron.[171] But in any case the estimate of the rate of ejection given by $\dot{M}_{SN} = (0.1 - 0.2) M_\odot/a$ seems to be reasonable.

Approximately the same value for the rate of ejection of matter by supernovae can be obtained from energy considerations.[166] The binding energy of the stable isotope Fe^{56} is $E \approx 60$ MeV, and therefore, assuming the amount of energy in the explosion to be $\mathscr{E} = (3 - 10)\cdot 10^{50}$ erg, we obtain the total number of Fe^{56} nuclei produced by one supernova as: $N_{Fe} \leqslant \mathscr{E}/E (3 - 10)\cdot 10^{54}$. In the case that the mass of the ejected shell is $M_{SN} = 1 - 10 \cdot M_\odot$ we have an upper bound estimate for the ratio of Fe^{56} to hydrogen (in terms of numbers of atoms) $Fe/H \leqslant (1 - 10)\cdot 10^{-4}$, which is close to that observed in cosmic rays.

In summary, the total rate of ejection by all the objects that have been considered amounts to $\dot{M}_e = 0.3 - 3 M_\odot/a$. The greater of these numbers corresponds to the maximum value of all the estimates quoted above taking the indefinitenesses into account. In particular, for the rate of loss of mass by close binary systems the assumed value was $M_m = 1.8 M_\odot/a$, which, as has been noted above, appears to be excessively large. Apparently, a more reasonable value for the total rate of ejection is $\dot{M}_e = 0.5 - 1 M_\odot/a$.

An independent estimate for $\dot{M}_e$ can be obtained by using theoretical calculations of the loss of mass by stars and the chemical composition of the ejected matter.[172–174] The rate of ejection of matter from stars is given by

$$\dot{M}_e = \int_{M_\odot}^{\infty} M_{er}(M)\,\Phi(M,\ t)\,\mathrm{d}M,$$

where $M_{er}(M)$ is the mass of the ejected matter, $\Phi(M,t)$ is the rate of formation of stars with the initial mass M in the galaxy of age t. Using the results of Ref. 175 for the initial spectrum of stellar masses and for the rate of star formation one can obtain $\dot{M}_e = 1\ M_\odot/\mathrm{a}$. It should be noted that the initial mass function for 750 stars of O type within a radius of 2.5 kpc from the sun as determined in Ref. 176 agrees well with the data of Ref. 175 within the mass range $M > 20M_\odot$. In Ref. 116 the rate of star formation $\Phi(M,t)$ was presented in the form of two different functions for spiral arms and for the space between the arms. Using more precise numerical parameters in the rate of star formation and using data on the luminosity of spiral arms leads the authors to the result $\dot{M}_e = 0.5 - 3M_\odot/\mathrm{a}$.

Let us now estimate the fraction of interstellar gas f which in the course of evolution of the galaxy has passed through stars. Let us consider the simplest model in which the rate of ejection of matter by stars $\dot{M}_e$ is proportional to the mass of all the stars in the galaxy $\dot{M}_e = \alpha M_s$, while the rate of transformation of gas into stars $\dot{M}_s$ is proportional to the mass of the gas $\dot{M}_s = \beta M_g$. The efficiency of ejection α can be determined knowing $\dot{M}_e$ and M_s at the present time. For $\dot{M}_e(\mathrm{now}) = 1\ M_\odot/\mathrm{a}$ and $M_s(\mathrm{now}) = 10^{11}M_\odot$ we obtain $\alpha = 10^{-11}\ \mathrm{a}^{-1}$. Similarly $\beta = \dot{M}_s(\mathrm{now})/M_g(\mathrm{now})$. Taking $M_g(\mathrm{now}) = 5\cdot 10^9 M_\odot$[177] and $\dot{M}_s(\mathrm{now}) = 2 - 4M_\odot/\mathrm{a}$ (cf., Ref. 175, 178), we obtain $\beta = (4-8)\cdot 10^{-10}\ \mathrm{a}^{-1}$. It is easy to show that the observed amount of deuterium d will at the present time t_1 be a fraction

$$\delta_1 = \delta(t_1) = \frac{(\alpha+\beta)\exp(-\beta t_1)}{\alpha+\beta\exp[-(\alpha+\beta)t_1]} \qquad (4.1)$$

of the pregalactic value d_0. Substituting into this α, β and $t_1 = 12\cdot 10^9$ a, we obtain $\delta = 5\cdot 10^{-3} - 0.5$. The lower value of δ corresponds to the larger value of β. As can be seen, small changes in the parameters significantly affect the ratios of the observed and pregalactic abundances of deuterium. Apparently this was the reason for the fact that in one of the variants of the model of the chemical evolution of the galaxy discussed in Ref. 116 the degree of destruction of deuterium in stars turned out to be equal to 20. But in such a case the pregalactic abundance of D must amount to $X = 4\cdot 10^{-4}$, which corresponds to the density of matter $\rho_m \lesssim 10^{-31}\ \mathrm{g/cm^3}$, which is less than the visible mass of the radiating matter. Moreover, such an estimate of X is incompatible with the value of the primordial abundance of helium $Y_p = 0.22 - 0.24$ assumed in the same article (cf., the data of Ref. 23). Such a low value of δ obtained by the authors Ref. 116 is related to the very great value assumed by them for the rate of star formation $10\cdot M_\odot/\mathrm{a}$, which corresponds to $\beta = 2\cdot 10^{-9}\ \mathrm{a}^{-1}$. This value exceeds, by at least a factor of three, estimates of other authors.[111,179] On the other hand in the models discussed in the same paper[116] with the rate of star formation of $\sim 3M_\odot/\mathrm{a}$ the problem of excessive destruction of deuterium does not arise.

Two low values of δ contradict the distribution of other elements in the galaxy. For example, it can be shown that the interstellar abundance of carbon C^{12} expressed in terms of numbers of particles is

$$[C^{12}] \approx 4.2\,[C^{12}]_\odot\,(1-\delta),$$

where the subscript $\odot$ corresponds to the solar abundance of C^{12}. In obtaining this estimate we have used the results of Ref. 172. From this it can be seen that the minimum allowed value of δ is equal to 0.75. A similar estimate for He^3

$$[He^3] \approx 2.2\,[He^3]_\odot\,(1-\delta)$$

yields $\delta \approx 0.5$.

We note, moreover, that the abundance of deuterium in the solar system exceeds by not more than a factor of two its abundance in the interstellar medium. This means that during the last $5\cdot 10^9$ a the amount of deuterium in the galaxy diminished by not more than a factor of two, i.e., the characteristic time for the burning up of D exceeds 5 billion years. Taking this into account and using the solution (4.1) we obtain limits on δ_1: $\delta_1 \geqslant 0.2$, if the age of the galaxy is $t_1 = 20\cdot 10^9$ a, $\delta_1 \geqslant 0.23$, if $t_1 = 15\cdot 10^9$ a, and $\delta_1 \geqslant 0.3$, if $t_1 = 12\cdot 10^9$ a. The values of β which satisfy these conditions are respectively equal to $2\cdot 10^{-10}$, $3\cdot 10^{-10}$ and $4\cdot 10^{-10}\ \mathrm{a}^{-1}$ (Fig. 9). The reason why these values of β differ from the observed ones at the present time ($\beta = 8\cdot 10^{-10}\ \mathrm{a}^{-1}$) consists, apparently, of the fact that at the earlier stages of the evolution of the galaxy the efficiency of conversion of gas into stars was lower than now. But at the same time the rate of star formation $\dot{M}_s = \beta M_g$ could significantly exceed the present value, and this corresponds to the socalled "bright phase" of the evolution of the galaxy.[142,143,180] Possibly the high efficiency of star formation β observed now is associated with the high content of heavy elements, with a spiral shock wave, etc.[181]

In order to make the presentation clear and graphic we have utilized for the calculation of the quantity δ the simplest model of chemical evolution of the galaxy. In more refined theories developed in Ref. 182 the estimate $\delta = 0.1 - 0.6$ was obtained with the larger value corre-

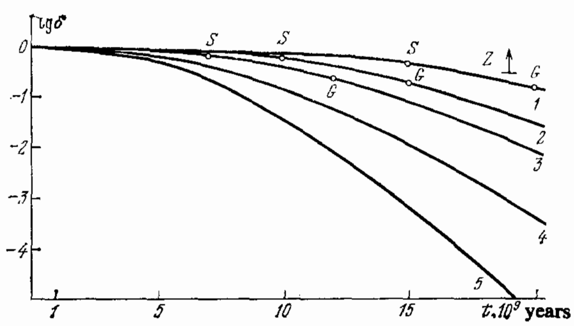

FIG. 9. Ratio of the abundance of D in the interstellar gas to the pregalactic abundance for different values of β. $\beta(\mathrm{a}^{-1}) = 2\cdot 10^{-10}$(1), $3\cdot 10^{-10}$ (2), $4\cdot 10^{-10}$(3), $8\cdot 10^{-10}$ (4), $1.6\cdot 10^{-9}$ (5). The points G indicate the possible age of the galaxy; S—the corresponding instant of birth of the solar system.

sponding to taking into account the accretion of the intergalactic gas by the galaxies; the subsequent refinement of the model made in Ref. 179 yields $\delta = 0.9$. It should be noted that the model of Ref. 179 was specially constructed to explain the observed specific features of the distribution of heavy elements in the galaxy.

b) Active processes in the galaxy and deuterium. Deuterium in the galaxy could be created in two ways: by thermonuclear fusion at high temperatures and by the reactions of breaking up of heavy nuclei by energetic particles. Fusion resulting in deuterium in the reaction $p + p \to D + e^+ + \nu_e$ requires approximately the same conditions as its burnup by means of the reaction $p + D \to He^3 + \gamma$, but the ratio of the rates of reactions

$$\frac{\lambda_{pp}}{\lambda_{pD}} \approx 1.6 \cdot 10^{-18} \exp(0.34 T_9^{-1/3}), \quad T_9 = \frac{T}{10^9}\ \mathrm{K}$$

is so small that the actual yield of deuterium in such processes is equal to zero.

In Refs. 183, 184, propagation of a shock wave originating in the explosion of a supernova through a low density medium was considered. The ions accelerated at the wave front will react with the "background" nuclei:

$$p + He^4 \to \begin{cases} D + n + p + p, \\ D + D + p, \\ D + He^3, \end{cases} \tag{4.2}$$

$$\alpha + He^4 \to \begin{cases} Be^8, \\ Li^7 + p, \\ Li^6 + p + p. \end{cases} \tag{4.3}$$

Rapid cooling of matter behind the shock-wave front will not allow the deuterium that has been formed to burn up into He^3. According to the calculations of Ref. 183, the efficiency of the mechanism is so great that it suffices for 10% of the interstellar medium to pass through shock waves from supernovae in order that the mass concentration of deuterium should attain the value $X = (1\text{–}2) \cdot 10^{-5}$. However, as was shown in Refs. 185, 186 as a consequence of the approximate equality of the rates of reactions (4.2) and (4.3) an excess of lithium will always arise in such processes, i.e., the ratio Li/D will always be by 2–3 orders of magnitude higher than the observed ratio. Therefore, in order not to produce a contradiction with the observed ratio of the abundances of lithium and deuterium it is necessary to assume that by this mechanism deuterium is produced in amounts not greater than $X \sim 10^{-7}\text{–}10^{-8}$. But if the energy of the shock waves is increased to 50 MeV/nucleon (and greater), all the nuclei will be broken up into individual nucleons and the process $p + n \to D + \gamma$ will become possible. The calculation of the chemical composition of the shells of supernovae carried out by the authors of Ref. 83, shows that a considerable enrichment of matter by deuterium with retention of the observed ratio of Li^7/D is possible if the energy of the supernova explosion is $E_{SN} > 10^{53}$ erg. But the ratio of the lithium isotopes turns out in this case to be excessively large: $Li^7/Li^6 > 10^3$. From this the following conclusions have been drawn[83]: in SN containing heavy elements (normal chemical composition) it is possible to obtain the required amount of Li^7 and B^{11}; in shells, which initially contained only hydrogen and helium, D or Li^7 can be synthesized with the yield of deuterium increasing as the energy of the explosion increases. The origin of the Li^6 and B^{10} isotopes should be explained by other mechanisms.

On the other hand, the observed energies of explosion of supernovae of both kinds are as a minimum lower by an order of magnitude ($E_{SN} < 10^{52}$ erg).[163] It is abundantly clear that the fraction of matter that has undergone reworking in ultraenergetic supernovae does not exceed 1%. All the difficulties which are encountered by attempts to synthesize deuterium in the shells of supernovae (overproduction of lithium, high energy of the explosion, etc.), are associated with the absence in the matter of free neutrons. Reference 187 takes into account the neutrino emission from the core of the SN and considers the following chain of reactions: $\bar{\nu}_e + p \to n + e^+$; $n + p \to D + \gamma$; $D + p \to He^3 + \gamma$, $He^3 + He^4 \to Be^7 + \gamma$, etc. The final composition of matter depends on the intensity of the neutrino flux and on the time of cooling of the shell, in which the above the reactions are taking place. For realistic models of the SN the yield of D without taking into account subsequent burnup is $x \leqslant 2\ 10^{-5}$, and taking burnup into account it is $x \leqslant 10^{-6}$ (cf., Fig. 8). Since the fraction of interstellar matter which has undergone reworking in supernovae is $f \leqslant 0.2$, it is clear that this mechanism cannot account for the entire observed mass of deuterium.

Free neutrons might arise as a result of the destruction of neutron stars. For example, in the review of Ref. 188 a relaxation process of the nonequilibrium layer which arises in the formation of a neutron star is considered which is accompanied by the liberation of energy with the possible ejection of free neutrons. If we assume that all the ejected neutrons become bound into D nuclei, then for the total mass of this isotope one can write the following equation:

$$\frac{dM_D}{dt} = 2\frac{dM_n}{dt} - \beta M_D,$$

where the last term βM_D takes into account the passage of deuterium into stars and the first term takes into account the entry of neutrons into the interstellar gas. Using the solutions for M_g and M_s obtained in Sec. 4c (Eqs. (4.5) and (4.6)) we can write the expression for the mass concentration of deuterium in the form:

$$X(t) = \frac{\alpha+\beta}{\beta} \cdot \frac{2}{M_\Gamma} \frac{dM_n}{dt}(1 - e^{-\beta t}) \times [\alpha + \beta e^{-(\alpha+\beta)t}]^{-1} + M_D^{(0)} \frac{e^{-\beta t}}{M_g};$$

here M_Γ is the mass of the galaxy ($\sim 10^{11} M_\odot$). Thus in order to obtain $X = 2 \cdot 10^{-5}$ during a time $t = 1.2 \cdot 10^{10}$ a it is necessary that $2 \cdot 10^{10}$ neutron stars should eject a part of the nonequilibrium layer of mass $\mu = 10^{28}$ g.[188] Moreover, since the lifetime of a free neutron is $\tau_n \approx 10^3$ s, a neutron star must be situated in a dense cloud in order that the neutron should have time to become captured by a proton to form a D nucleus. According to present day observations of pulsars and supernovae the frequency of formation of neutron stars does not exceed $1/27\ a^{-1}$, so that their total number in the galaxy must be smaller than 10^9.[182,183] Apparently such processes will give rise to heavy elements enriched in neutrons rather than deuterium.

As has been noted already, the intensity of cosmic rays in the galaxy at the present time is insufficient to produce the observed concentration of deuterium.[78] However, in its early years the galaxy could have been more active, and then the flux of cosmic rays could have exceeded the present one by a factor of 10–100. Reference 190 considers the process $p + He^4 \to 2D + p$, brought about by energetic protons born within the active core of the galaxy. Since the binding energy of the He^4 nucleus is $E_m \approx 200$ MeV, in order to produce the observed concentration of deuterium one requires, as has been shown in Ref. 190, $> 3\cdot 10^{59}$ erg in the form of cosmic rays, and this is, apparently, too much. One should also take into account the fact that α-particles will be accelerated as well as protons, i.e., overproduction of lithium will necessarily result.[185,186,190] The model for the production of deuterium by the photodisintegration of He^4 which was proposed in Ref. 191 suffers from still greater energy difficulties.

At the same time, if all the mechanisms described above did indeed give rise to a significant production of deuterium, a correlation should be observed between the frequency of explosions of supernovae and the concentration of pulsars with the distribution of D in the galaxy. But the observations of Ref. 117 indicate a positive gradient for the abundance of deuterium, while the supernovae and the pulsars are concentrated towards the core of the galaxy.[192] The arguments presented above give rise to considerable doubt concerning the possibility of explaining the observed distribution of deuterium by active processes in the galaxy.

An interesting mechanism for the generation of deuterium is proposed in a recent paper.[193] In a hot two-temperature accretion disk formed in the course of accretion of matter onto a relativistic object (neutron star, black hole) which forms a part of a binary system, the occurrence of thermonuclear reactions with the production of free neutrons is possible. These neutrons can be captured by protons directly within the disk itself and form D nuclei with a relative concentration $d \sim 10^{-3}$. But, because of the presence of a sufficiently great thermal velocity ($T_1 \geqslant 5$ MeV), a fraction of the neutrons can evaporate from the surface of the disk and will be captured by the protons either in dense cold clouds surrounding the disk or within the atmosphere of the normal companion star. In the latter case the stellar wind will carry the deuterium being formed into the interstellar medium. This variant of the synthesis of D is free from difficulties associated with the overproduction of lithium. A direct proof of the realization of the mechanism considered above would be the observation of the γ-line $E_\gamma = 2.2$ MeV which arises in the reaction $p + n \to D + \gamma$. Unfortunately, in the absence of data on the distribution of such binary systems in the galaxy and concerning their number, it is not possible at the present time to calculate the contribution of the above process to the interstellar abundance of deuterium.

c) Accretion of intergalactic gas onto the galaxy. Until now we have neglected the accretion of intergalactic medium IGG onto the galaxy, but simple estimates indicate that the influx of gas from intergalactic space can be quite significant. Indeed, according to Ref. 194 the rate of accretion is

$$\dot{M} = 0.8 \frac{\rho_{28}}{(C_{200}^2 + V_{200}^2)^{3/2}} \left(\frac{M_\Gamma}{10^{11} M_\odot}\right)^2 \quad M_\odot/\mathrm{a}, \qquad (4.4)$$

where $\rho_{28} = \rho/10^{-28}$ g/cm^3 is the density of the intergalactic gas, $V_{200} = V/200$ km/s is the velocity of the galaxy, M_Γ is its mass, $C_{200} = C/200$ km/s is the speed of sound in IGG.

The density and the temperature of the IGG can be determined from the thermal bremsstrahlung of hot electrons that falls within the x-ray range. At the centers of highly populated clusters Perseus, Coma, Hercules, according to the observations of "Uhuru" the values are $\rho_{28} = 30$–40, $T = 10^8$ K.[17] In the neighborhood of our galaxy the density of IGG is not known, but for an estimate one can assume $\rho_{28} = 0.1$–1. According to measurements of dipole anisotropy of the relict radiation and the x-ray background the velocity of the galaxy is $V = 200$–300 km/s. Then from (4.4) we obtain $\dot{M} = 0.05 - 0.8 M_\odot/\mathrm{a}$. The lower bound on $\dot{M}$ agrees well with the results of Ref. 195 obtained using x-ray radiation of the gas of the corona. Analysis of the dynamics of high velocity clouds of neutral hydrogen led the authors of Ref. 196 to a value for the rate of accretion which is several times greater. This means that the entire interstellar gas observed at the present time could have originated as a result of accretion of the IGG. Tinsley and Danly[197] analyzing the intensity and the spectrum of the radiation from young spiral galaxies arrived at a similar conclusion, since the rate of formation of stars within them is so great that the entire primordial gas, is "eaten up" during 0.25 of the Hubble time. However, since the observed mass of the interstellar gas amounts to only a few percent of the total mass of the galaxy and of the young galaxies that have been investigated, the determination of this quantity on the basis of the measurements of the "mass-luminosity" and "color-luminosity" relationships which are subject to great inaccuracies, appears to be unconvincing.

The change in the masses of the stellar and gaseous components of the galaxy taking accretion into account is described by the equations:

$$\frac{dM_g}{dt} = -\beta M_g + \alpha M_s + \dot{M},$$

$$\frac{dM_s}{dt} = \beta M_g - \alpha M_s.$$

When $t = 0$ $M_g = M_0$, $M_s = 0$. The solution of this system of equations on the assumption $\dot{M} = \mathrm{const}$ has the form

$$M_g(t) = M_0 \frac{\alpha + \beta e^{-(\alpha+\beta)t}}{\alpha+\beta} + \dot{M} \frac{\alpha t + \beta\left(1 - e^{-(\alpha+\beta)t}\right)/(\alpha+\beta)}{\alpha+\beta}. \qquad (4.5)$$

Since, as follows from observations, $\beta \gg \alpha$ and $(\alpha + \beta)t > 1$, the mass of the interstellar gas due to accretion is

$$\Delta M_g(t) \approx \dot{M}\left(\frac{\alpha}{\beta} t + \frac{1}{\beta}\right).$$

Assuming $\beta = 3\cdot 10^{-10}$ a^{-1} and $\alpha = 10^{-11}$ a^{-1}, $t = 1.2\cdot 10^{10}$ a and $\dot{M} = 1 M_\odot/\mathrm{a}$, we shall obtain $\Delta M_g \approx 3.5\cdot 10^9 M_\odot$, i.e., $\Delta M_g \approx 0.7 M_g$. In its turn the mass of the stellar component is

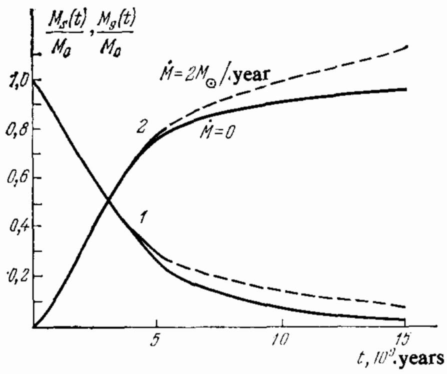

FIG. 10. The masses of the stellar and gaseous components of the galaxy as a function of the time. The lines are marked with the inflow of mass as a result of accretion. 1—$M_g(t)/M_0$, 2—$M_s(t)/M_0$.

$$M_g(t) = \frac{\beta M_0}{\alpha+\beta}\left[1 - e^{-(\alpha+\beta)t}\right] + \frac{\beta \dot{M}}{\alpha+\beta}\left[t - \frac{1-e^{-(\alpha+\beta)t}}{\alpha+\beta}\right]. \qquad (4.6)$$

As can be seen from the calculations outlined above (and also from Fig. 10) as a result of the relation $\Delta M_g < M_g$ accretion practically does not affect the rate of star formation, but the average rate of star formation during the first $5\cdot10^8$ years exceeds by approximately a factor of 4, and during $5\cdot10^9$ years exceeds by approximately a factor of 2 the rate during $12\cdot10^9$ years. Since the first stars have a luminosity several orders of magnitude greater than that of the sun (cf., Sec. 3), the approximately 15% of the matter of the photogalaxy which evolved into stars during $5\cdot10^8$ years are sufficient to provide for the energy output of the young galaxy, which exceeds the present-day energy output by a factor of 10–100.

If one assumes that the accreting IGG has the primordial chemical composition the fraction of the present-day interstellar gas which has been subjected to thermonuclear burnup in stars can be estimated as

$$f = 1 - \frac{M_0 e^{-\beta t} + \dot{M}(1 - e^{-\beta t})/\beta}{M_g}.$$

When $t = 1.2\cdot10^{10}$ a and $\dot{M} = 2M_\odot/\mathrm{a}$ $f = 0.28$, i.e., when the rate of accretion is $\dot{M} \gtrsim 2\,M_\odot/\mathrm{a}$ the abundance of deuterium in interstellar gas practically does not differ from the cosmological abundance. Quite recently iron lines have been observed in the IGG.[198,199] According to the estimates of Ref. 200 the abundance satisfies $\mathrm{Fe/H} \lesssim 3\cdot10^{-5}$ which is only severalfold lower than the solar abundance. Possible mechanisms of enriching the IGG by heavy elements are discussed in Ref. 201, but in any case the variant in which a significant part of IGG would be subjected to thermonuclear burnup should be excluded. On the other hand, a high rate of ejection of gas from the galaxy can prevent accretion entirely.[202,204] In this connection simultaneous observations of the spectrum of thermal bremsstrahlung from the IGG and K_α-lines of iron in galactic clusters become particularly urgent.[205]

CONCLUSION

The existing theoretical concepts and observational data enable us to analyze the problem of the origin of deuterium. The principal conclusion that follows from this analysis consists of the fact that firstly the active processes in the pregalactic stage of the evolution of the universe associated with the activities of the so-called "prequasars" are able to produce deuterium to an extent not greater than $X \sim 10^{-7}$, i.e., the primordial abundance of deuterium in the galaxy was equal to its cosmological abundance. Secondly, nonequilibrium phenomena in the galaxy, such as the activity of the galactic core, the explosion of neutron stars and shock waves accompanying the explosion of supernovae yield not more than one percent of the observed amount of deuterium, and therefore in the process of evolution of the galaxy the abundance of deuterium can only be diminished due to its being burned up in the stars. An estimate of the degree of destruction of this isotope (a decrease by a factor of 3–5) indicates that the standard model of the universe with $0.05 \leqslant \Omega_m \leqslant 0.08$ agrees with the observed galactic abundance $X = (2\text{–}3)\cdot10^{-5}$. Apparently, other cosmological models can also be considered satisfactory if the yield of deuterium in them lies within the range $X = (3\text{–}15)\cdot10^{-5}$.

The problem of the origin of deuterium lies within the framework of the general problem of the origin of light elements. At the present time the isotopic composition of lithium remains unexplained. It can be expected that a future exhaustive investigation of mechanisms that determine the isotope ratio Li^7/Li^6 in the galaxy will enable us to make our concepts of the evolution of the abundance of deuterium more precise. To some extent the problem of the origin of the remaining chemical elements is associated with this. The construction of a more detailed picture of the evolution of the abundances of the chemical elements, and in particular deuterium, requires new data on the rate of ejection of matter from a star, on its chemical composition, on the nature of star formation at the early stages of the evolution of the galaxy and on the interaction of the galaxy with the intergalactic gas.

Recently interesting articles have appeared which contain both new ideas concerning the origin of the light elements and also a new interpretation of the available observational data.

In Ref. 211 on the basis of the latest data on the cross sections of nuclear reactions a calculation has been made of the yield of light elements in the standard cosmological model over a wide range of variation of specific entropy. A significant deviation (factor ~ 2) from the results of Ref. 23 has been obtained only for Li^7. In the opinion of the authors of Ref. 211 the allowable values of the specific entropy are $s = (1\text{–}3)\cdot10^9$ and this agrees with the values of Ω_m quoted by us earlier. The attempt to find a lower limit on Ω_m from the calculations of the yield of He^4 and their comparison with observations undertaken in Ref. 211 appears to us to be unrealizable at the present time. We must once again emphasize the necessity of taking into account the evolution of the abundances of light elements in the course of the life of the galaxy. New observations[212] of the abundance of He^3 in H II regions in the neighborhood of the sources W3, W51, W43 support the value $He^3/H = 2\cdot10^{-5}$ in the interstellar medium, which agrees well with the results of calculations of cosmological nucleosynthesis with $\Omega_m < 0.1$.

The decay of massive leptons the existence of which is predicted by present-day theories of elementary particles can occur with the emission of electron neutrinos and antineutrinos. In Ref. 213 a calculation is made of the yield of deuterium and He^3 in the standard cosmological model with decaying heavy leptons and it is shown that even for $\Omega_m = 1$ it is possible to obtain the observed abundance of D if the mass of the leptons is 10–100 MeV, while their lifetime is $\tau_H = 10^3$–10^4 s. The growth of the abundance of D is due to the following chain of reactions: $\bar{\nu}_H \rightarrow \bar{\nu}_e + e^+ + e^-$; $p + \bar{\nu}_e \rightarrow n + e^+$; $p + n \rightarrow D + \gamma$. However, the massive leptons as a result of their energy density accelerate the rate of cosmological expansion of the universe, and this leads to an increase in the quenching temperature and, consequently, to an increase in the yield of He^4. The decay of these leptons generates additional entropy, i.e., the synthesis of He^4 occurs at lower values of s, and this means that this yield increases even more. It can be shown that these two factors increase the abundance of helium to values that contradict the observed values in objects with a low metal content.

As the authors of Ref. 190 noted for the first time, there does not exist such a single value of Ω_m for which one could satisfactorily explain the observed abundances of D, He^3, He^4, Li^7 by means of cosmological nucleosynthesis. It is true that if the latest observations[214] of lithium in old objects indeed do reflect its pregalactic abundance, the situation is changed somewhat.[215] But in any case the required abundance of D can be obtained only if $\Omega_m < 0.1$.

A radically different scenario for the origin of light elements is proposed in Refs. 216, 217. In the model of Ref. 216 the cosmological substratum is pure hydrogen in which massive stars ((100–1000) $M_\odot$) are formed with red shifts of $z \gtrsim 100$. The explosions of these stars accelerate the α-particles synthesized within them to energies of $E \gtrsim 100$ MeV as a result of which deuterium is formed in the interstellar gas in the reaction $\alpha + p \rightarrow D + \ldots$. The remaining helium is ejected into the surrounding space with considerably lower energies per particle. In this model it is difficult to avoid the previously noted defects of all the schemes of nonequilibrium synthesis of deuterium, in particular, the overproduction of lithium and the large liberation of energy.

One should also note Ref. 218 in which a thorough analysis of the composition of the Murchison meteorite is made. The results of this analysis show that in the cold protosolar cloud significant chemical fractionation occurred so that observations of deuterated molecules in the solar system cannot be directly used to estimate the content of deuterium in the interstellar medium five billion years ago.

A detailed review of new results and unsolved problems relating to the chemical evolution of the galaxy is given in Ref. 219.

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1) The abundances of the elements are determined with the greatest degree of confidence in the matter of our and neighboring galaxies; deuterium is visible only in our galaxy.

2) The concept "insignificantly" for deuterium signifies a possible change of the abundance by a factor of 2–3, for helium by several percent.

3) The parameter Ω characterizes the ratio of the total density of gravitating matter, including massive neutrinos and other particles which are difficult to observe, to the critical density ρ_{cr}.

4) The retardation parameter is $q = R\ddot{R}/\dot{R}^2$, where $R(t)$ is the scale factor in the Friedmann model; at the present stage of the evolution of the universe we have $q = \Omega/2$. We restrict ourselves to a consideration of models with the cosmological constant Λ equal to zero.

5) The red shift of spectral lines due to the expansion of the universe is $\Delta\lambda/\lambda = z + 1$, T.e. $R(t_0)/R(t) = z + 1$.

6) An exception are some types of stars which have bared their deep lying portions in the course of evolution and which are characterized by anomalies of their chemical composition (cf., below).

7) The parameter Ω is defined by the ratio of the total density of gravitating matter to the critical density.

8) The quantity d determines the concentration of deuterium with respect to hydrogen in terms of the number of particles. The mass concentration is $X = 2d\,[1 - (Y/4)]$.

9) He^3 was also observed in the region H II in the neighborhood of the source W51. The relative content is $He^{3+}/H^+ = (4 \pm 1)\cdot 10^{-5}$.

10) According to the estimates in Ref. 104 up to 80% of the mass of the interstellar gas can be contained within such clouds.

11) The gradient is determined by the destruction of D within the region of intense star formation in the neighborhood of the galactic center (cf., also Ref. 120).

12) Mezger[127] found a negative gradient of He^4. According to observations on planetary nebulae a negative gradient of He, O, N, has been found.[128–132] The existence of a negative gradient of the concentrations of He^4 and heavy elements agrees well with existing concepts concerning their synthesis in stars (He^4 in insignificant quantities) and their later ejection into the interstellar medium. Therefore in the region of intense star formation at the center of the galaxy the concentration of He^4 and heavy elements is higher. However, due to large observational error and the indefiniteness of a number of required parameters (density of stars of different spectral classes, the rate of ejection, etc.), the results of the calculations of the magnitude of the gradient are appreciably different in the case of different authors.

13) According to the calculations of Ref. 141 the masses of the first stars are $\sim 10\, M_\odot$.

14) It is also not clear from what type of perturbations, with what amplitude and spectrum can these "prequasars" be formed with such large red shifts $z > 300$. In Ref. 144 it is shown that the "prestars" with $M = 10^5$–$10^6\, M_\odot$ could be formed in the hot model with $z \approx 20$.

15) Stars eject matter either by means of protracted quasistationary ejection (stellar wind), or in flares accompanied by formation of a white dwarf or a neutron star. In the latter case deuterium can be produced in hot regions behind the shock-wave fronts only in insignificant amounts (cf., below).

16) According to the standard terminology—supergiants of the spectral class M.

17) Stars of the main sequence of the spectral classes O and B.

18) Observations of Refs. 156, 157 agree well with the theoretical calculations of Ref. 158.

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