What can deuterium tell us?

The recently observed relative abundance of this isotope in our galaxy may be a remnant of the fireball phase of the universe.

David N. Schramm and Robert V. Wagoner

What is behind the unusual flurry of activity concerned with the isotope deuterium? Simply this: Because of its unique properties, the distribution of deuterium in the universe constitutes a powerful clue to the history of the development of matter.

New instruments and techniques have given us good measurements of the ratio of deuterium to hydrogen at various astrophysical locations. When we examine how deuterium can be produced and destroyed in nuclear reactions, we will see what the implications of these abundance figures are to the study of its origins and evolution.

The ratio of deuterium to hydrogen and other nuclides on Earth and in interstellar space is much larger than could have been produced from ordinary stars such as our Sun. This deuterium abundance could only have been produced in violent events such as supernova explosions or in the big-bang fireball. However, comparison with the abundances of other light elements appears to make supernova shock waves unlikely sites for the origin of deuterium. It appears likely, then, that the large amount of deuterium observed was synthesized in the first few minutes of the expansion of the universe.

Observations of deuterium abundance

The observed helium abundance supports the standard general-relativistic model of the universe. Within this model, the deuterium abundance sets an upper limit to the average matter density of the universe, which can help us determine whether the universe is finite or infinite. The data available favor the infinite universe.

Table 1 summarizes the current state of the observations of deuterium. An important quantity is the numerical abundance ratio, D/H, of deuterium atoms to hydrogen atoms. With a helium abundance ratio, He^4/H, of about 0.1, the fraction, X(D), of deuterium mass to total mass, is about 1.4 D/H when hydrogen and helium are the main constituents.

It has been known for a long time[1,2] that water on Earth and in carbonaceous meteorites contains deuterium in the ratio of 150 ppm to hydrogen. We have also known that stars like the Sun should have converted essentially all of the deuterium in their outer regions to helium-3 via the nuclear reaction

$$D + p \longrightarrow He^3 + \gamma$$

The observations of an upper limit on D/H of 4 ppm for the Sun was thus not surprising. However, an inspection of the references in Table 1 reveals that the bulk of the astronomical deuterium measurements (which have taken place within the past two years) indicate an abundance level that is certainly different from the previously accepted value. As we will see, it now appears that deuterium constitutes about 14 ppm of the hydrogen in the interstellar gas near the Sun.

The first of the recent measurements was performed by the Apollo 11 astronauts on the Moon. As you may recall, an experiment performed on that flight consisted of lowering an aluminum foil "window shade" to collect the solar wind. Subsequent mass-spectrometric analyses of this and other Apollo experiments in Johann Geiss's laboratory in Bern, Switzerland, revealed that the ratio of He^3 to He^4 in the solar wind is $(4–5) \times 10^{-4}$. The assumption that, for the Sun, $He^4/H \leq 0.10$ then makes He^3/H less than 5×10^{-5}. Since some of this He^3 might have come from the conversion of deuterium by the Sun, this implies that D/H is less than 50 ppm in the gas from which the Sun formed, the protosun. This value is significantly less than that observed in the Earth's ocean water. The difference can be understood by chemical fractionation: In the formation of water, D is selected preferentially relative to H—the large mass ratio of the hydrogen isotopes allows them to have different chemical as well as nuclear properties.

After determining this upper limit on D/H, Geiss and Hubert Reeves[8] attempted to determine an actual value. They estimated that the protosolar value of He^3/H was comparable to that of D/H. Noting that

$$(D/H)_{\text{protosolar}} = (He^3/H)_{\text{present}} - (He^3/H)_{\text{protosolar}}$$

they concluded that D/H $\approx$ 25 ppm. This estimate was supported on independent grounds by the meteorite work of David Black,[6,7] who showed that the various rare-gas components of gas-rich meteorites have a solar-wind helium isotope ratio comparable to that observed by Geiss but, in addition, a presumed primordial component with $He^3/He^4 \approx 1.5 \times 10^{-4}$. This led Black to his

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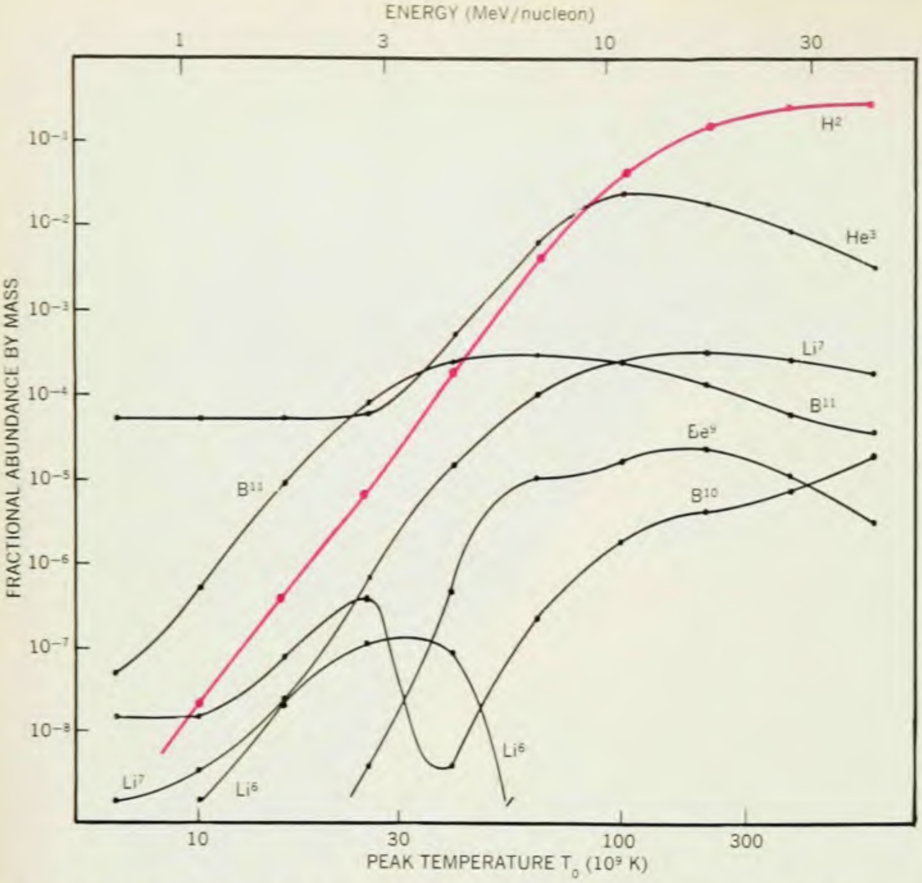


The dependence of the final abundances, after all decays, of various nuclides on the maximum temperature T_0 and on the energy per nucleon to which the gas has been heated by a supernova shock wave. The dots indicate the actual results. The rising curve for deuterium (shown in color) implies that it is produced most rapidly in higher-energy shocks. Figure 2

result for deuterium given in Table 1, which is quite consistent with, and totally independent of, the estimate of Geiss and Reeves. Subsequently, Donald Hall of Kitt Peak National Observatory found the unpublished result that He^3/He^4 in solar prominences was $(4 \pm 2) \times 10^{-4}$, quite in line with the solar-wind values. Since there is always a question as to whether solar-wind abundances are representative of the Sun (in fact, Geiss's observations show a small dependence on geomagnetic conditions), this observation of Hall's clearly removed any doubts that the protosolar abundance of deuterium was less than the terrestrial value.

A solar-system observation that also indicated chemical fractionation of deuterium was the detection of deuterated methane, CH_3D, in Jupiter by Reinhard Beer and Fredric Taylor.[3] The range of values for D/H given in Table 1 reflects the uncertainties involved in the analysis of Jupiter's atmospheric structure and deuterium fractionation. More recently John Trauger and his coworkers[4] used observations of molecular hydrogen to obtain $D/H \approx HD/2H_2 = (21 \pm 4)$ ppm for the Jovian atmosphere. Since the bulk of the hydrogen and deuterium in Jupiter should be in the form of H_2 and HD, this result is less model-dependent. Alastair Cameron,[16] feeling that Jupiter's atmosphere should have a composition representative of that of the protosolar nebula, adopted this value of D/H in his latest abundance table. This represents the best estimate of the abundance of deuterium 4.6×10^9 years ago, when the Sun formed.

In addition to these solar-system abundance determinations, there have also been a large number of recent observations of deuterium in the interstellar medium. Previously, the most significant result was the upper limit of 70 ppm set on D/H by Sander Weinreb.[9] In this observation, he looked in the direction of the radio source Casseopeia A for absorption by the 91.6-cm deuterium hyperfine line (the deuterium equivalent of the famous 21-cm hydrogen line) but did not find any. Diego Cesarsky, Alan Moffet and Jay Pasachoff[10,11] recently applied a similar technique to the radio source Sagittarius A in the galactic center and obtained a possible detection. The resulting upper limit on the deuterium abundance is also given in Table 1.

The first certain detection of interstellar deuterium was obtained by Keith Jefferts, Arno Penzias, and Robert Wilson[12,13], who observed deuterium cyanide in the Orion Nebula molecular cloud. Unexpectedly, the DCN–HCN ratio was 40 times greater than the terrestrial D–H ratio. It soon became clear, however, that chemical fractionation favoring DCN formation over HCN formation prevents any simple relationship to the total deuterium abundance. The Copernicus satellite[14] later observed values of interstellar HD/H_2 of about 1 ppm or greater in front of nine stars. In these molecular clouds, the shielding of H_2 in the central regions against photodissociation by its outer layers enhances the presence of H_2, while chemical fractionation enhances the abundance of HD relative to H_2. A number of people[17,18,19,20] have investigated the problem of determining the total abundance of interstellar deuterium from deuterated molecular abundances. Their results at least indicate that the DCN/HCN and HD/H_2 observations are consistent with an interstellar value of D/H of about 10 ppm.

Finally, the determination of interstellar deuterium abundances was "cleaned" of all this chemistry and other theoretical uncertainties by the direct observations with the Copernicus satellite (Figure 1) of the Lyman series transitions of atomic deuterium. Using the L β, γ, δ, and ϵ lines, John Rogerson and Donald York[15] determined that $D/H = (14 \pm 2)$ ppm in the direction of the star Beta Centauri. At the 1974 Chicago meeting of the APS, York reported that this value was consistent with the results obtained by observing seven other nearby (closer than 1 kpc) stars. These beautiful observations conclusively show that a significant fraction, $X(D) = 2 \times 10^{-5}$, of the mass of the interstellar medium in the neighborhood of the Sun is now in the form of deuterium.

In discussing the origin and evolution of the light elements, Reeves, Jean Audouze, William Fowler and Schramm[21] predicted, primarily on the basis of solar-wind observations, that $D/H \approx 10$ ppm in the present interstellar medium. These results certainly appear consistent with that prediction. In the next sections, we will examine how deuterium can be produced and destroyed and thus learn what the study of its origin and evolution can tell us.

Deuterium production and destruction

Within normal hydrogen-burning main-sequence stars such as our Sun, deuterium is produced via the weak reaction

$$p + p \longrightarrow D + e^+ + \nu_e$$

However, the deuterium produced by this reaction is rapidly burned by the much faster reaction

$$p + D \longrightarrow He^3 + \gamma$$

which, as mentioned earlier, results in a very small equilibrium abundance of D. For the same reason all the deuterium present in the interstellar material that condenses into a star will soon be destroyed. Models of galactic evolution[22,23] indicate that 30–70% of the present interstellar gas has been processed through a star at least once. However, because of the uncertainties involved, we limit ourselves to the more conservative conclusion that any deuterium present when the galaxy formed would have been reduced in abundance by now.

Deuterium can also be synthesized via the reaction

$$p + n \longrightarrow D + \gamma$$

This reaction does not involve the weak interaction, nor is it inhibited by a Coulomb barrier. However, it does require free neutrons, which are not found in typical astrophysical sites because of their instability. To produce copious quantities of free neutrons requires *high energy,* as we shall see in the next section, where we discuss possible production sites.

Deuterium can also be formed as a product of spallation reactions, the most important of which is

$$p + He^4 \longrightarrow D + He^3$$

with a threshold center-of-mass energy of 18.35 MeV. Such reactions require *high energy* because the binding energies of the products are usually much less than the binding energies of the more abundant colliding nuclei.

In searching for appropriate astrophysical conditions, one must keep in mind that deuterium is easily destroyed by the reactions

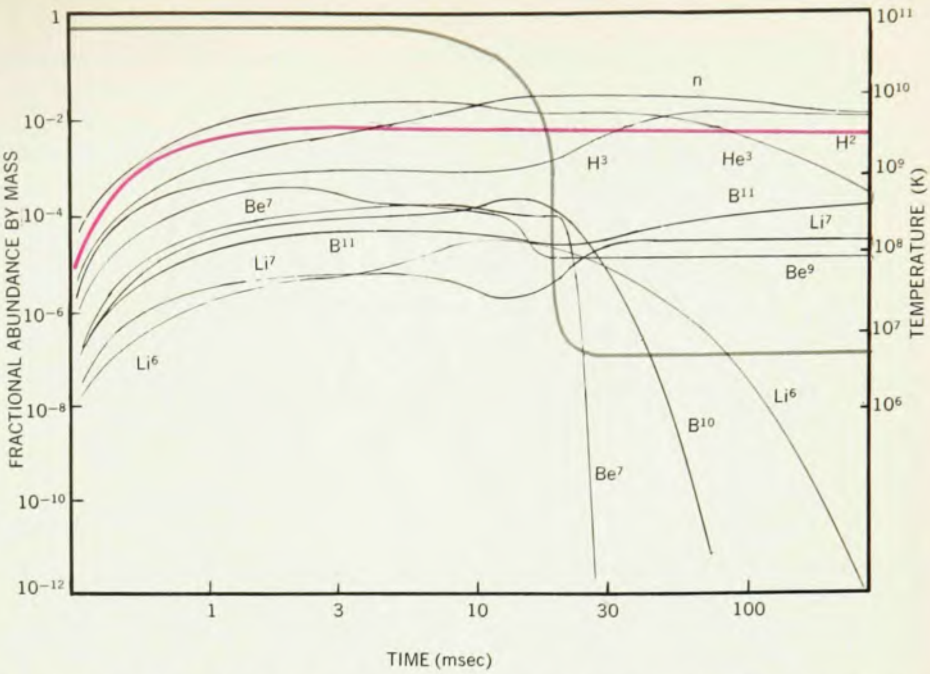
$$D + D \longrightarrow n + He^3$$
$$D + D \longrightarrow p + T, \text{ and}$$
$$n + D \longrightarrow T + \gamma$$

if the deuterium or neutron *density* is high enough, as well as by the proton reaction if its *density* is high enough.

Thus it appears certain that the deuterium in the universe today was produced in environments with *high energy* (to make it) and *low density* (to avoid its destruction). In what environments are these conditions found?

Possible astrophysical production sites

The constraints mentioned in the previous section severely limit possible sites for deuterium production. One possibility might be matter bombarded by high-energy particles. In the early 1960's deuterium and the light elements lithium, beryllium and boron were thought to have been formed in high-energy particle irradiations of the early solar system by the then active Sun.[24] However, experimental study of meteorites revealed no evidence for such a flux of particles,[21] and the energies available in the early Sun are now thought to have been far less than those required.[25]



The evolution in time of the ion temperature (gray curve) and the abundances of neutrons, deuterons (in color) and other light nuclei produced in a supernova shock of peak temperature $T_0 = 10^{11}$ K. After the shock passes, the temperature drops rapidly to about 10^7 K. Figure 3

Table 1. Observed ratio of deuterium to hydrogen atoms

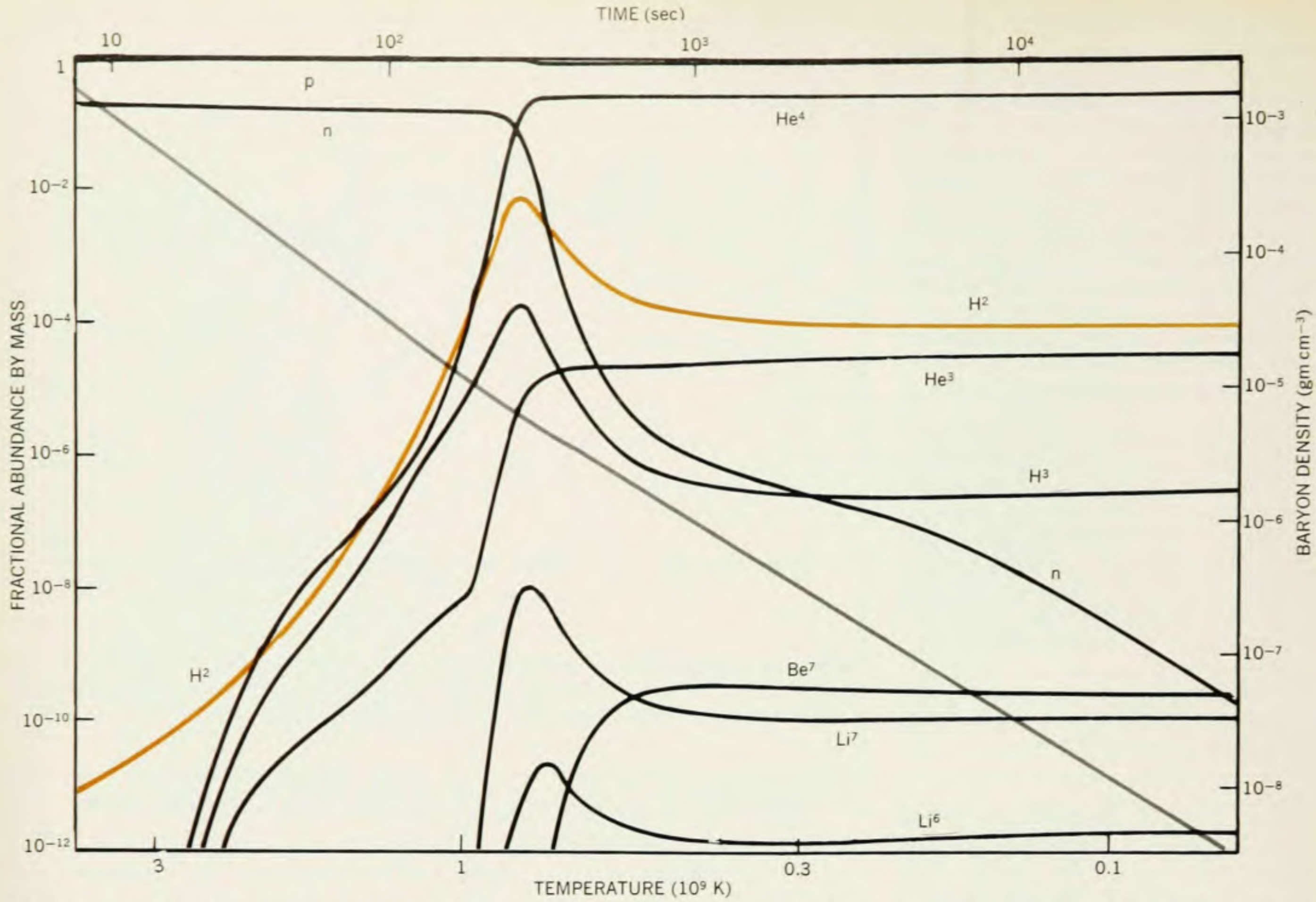
Location	$(D/H) \times 10^5$	Observer
Solar system:		
Earth (HDO)	15	Friedman et al, 1964[1]
Meteorites (HDO)	13–20	Boato, 1954[2]
Jupiter (CH_3D)	2.8–7.5	Beer, Taylor, 1973[3]
Jupiter (HD)	2.1 ± 0.4	Trauger et al, 1973[4]
Present Sun	<0.4	Grevesse, 1970[5]
Primordial Sun		
from He^3 in gas-rich meteorites	1–3	Black, 1971[6]; 1972[7]
from He^3 in solar wind	<5	Geiss, Reeves, 1972[8]
from He^3 in solar prominences	<6	Hall, unpublished
Interstellar medium:		
Cassiopeia A (91.6-cm line)	<7	Weinreb, 1962[9]
Sagittarius A (91.6-cm line)	<35	Cesarsky et al, 1973[10,11]
Orion Nebula (DCN/HCN $= 6 \times 10^{-3}$)	*	Jefferts et al, 1973[12,13]
Nearby clouds ($HD/H_2 \gtrsim 10^{-6}$)	†	Spitzer et al, 1973[14]
β Centauri ($L\beta$, γ, δ, ϵ lines)	1.4 ± 0.2	Rogerson, York, 1973[15]

* Uncertain because of chemical fractionation.
† Uncertain because of self-shielding and chemical fractionation.

Table 2. Production by galactic cosmic rays

Nucleus	Observed mass fraction*	Calculated/observed
D	2×10^{-5}	$<10^{-2}$
He^3	3×10^{-5}	$<10^{-2}$
He^4	3×10^{-1}	negligible
Li^6	4×10^{-10}	1
Li^7	6×10^{-9}	10^{-1}
Be^9	1×10^{-10}	1
B^{10}	7×10^{-10}	1/2
B^{11}	3×10^{-9}	1/2
$A \geq 12$	2×10^{-2}	made in stars†

* From reference 16 except for boron and deuterium; these are known to within a factor of 2 with the possible exception of boron; see note in Table 3.
† With the possible exception of a few rare nuclei.



The expansion of the universe under a typical standard big-bang model. The baryon density (in gray) and nuclear abundances (with deuterium in color) are traced in time and as a function of temperature; the present baryon density was taken as 2.3×10^{-31} gram/cm^3. After the deuterium abundance rises to about 10^9 K, it becomes depleted in the synthesis of heavier nuclei such as Be and Li. Figure 4

The galactic cosmic rays, on the other hand, constitute an observed source of high-energy particles. As these cosmic rays bombard the interstellar gas, spallation reactions occur, including some that produce deuterium. Reeves, Fowler and Fred Hoyle[26] first showed that the effect of this irradiation, when integrated over the age of the galaxy, could account for the observed abundances of Li^6, Be^9, B^{10} and possibly B^{11}. However, such a process produces less than 1% of the required amount of deuterium (and also fails for the other light nuclei He^3, He^4 and Li^7). Table 2 summarizes the current status of such calculations,[27,28] which, it should be emphasized, are based on the *measured* cosmic ray fluxes and interstellar densities of the most abundant elements, and (mainly) *measured* spallation cross sections. It should also be mentioned here that if the boron abundance were as large as Cameron[16] recently proposed then the good agreement for that element indicated in Table 2 would no longer exist. However, other recent analyses[29] tend to favor the lower boron abundances we have assumed in Table 2. In addition, recent Copernicus satellite observations[30] indicate that the gas in the interstellar medium may be depleted in boron with respect even to the value shown in Table 2. Possibly the boron is trapped in grains.

D from supernova shock waves?

A potentially more promising location in which sufficiently high energies and low densities might be found is supernova shock waves. Stirling Colgate[31,32,33] and, independently, Hoyle and Fowler[34] showed that such shocks might be energetic enough to break helium-4 up into deuterium or nucleons that could later recombine to form deuterium. We will now calculate, from the energy requirements on this process, the amount of matter which had to have been exposed to such strong shocks.

Applying the conservation laws across the shock wave tells us that the internal energy per unit mass developed behind the shock is given by $U = V^2/2$, where V is the velocity of the gas behind the shock relative to the (stationary) gas in front of the shock. In order that the random kinetic energy U be sufficient to break up He^4, V has to be greater than about 4×10^4 km/sec. The velocity V will increase as the shock proceeds outward if the density decrease in the stellar envelope is sufficiently steep. Therefore the fraction F_c of the mass of the star exposed to velocities $V \geq V_c$ would be a decreasing function of V_c. This function was given by Colgate as $F_c \propto V_c^{-4}$ or, in terms of ϵ_c, the final ejected kinetic energy per nucleon, as

$$F_c = \frac{3}{7}\left(\frac{\epsilon_0}{\epsilon_c}\right)^2 \qquad (1)$$

The constant ϵ_0 in a given star is related to the kinetic energy W_0 and the mass M_0 of the total amount of ejected matter by $W_0 \equiv 6M_0\,\epsilon_0/5m_u$, where m_u is the proton mass. Equation 1 is valid for values of ϵ_c/ϵ_0 ranging from 1 to 100. Various supernova models predict $0.1 \lesssim \epsilon_0 \lesssim 10$ MeV/nucleon. We also know that $\epsilon_c = 2m_u V_c^2 \approx 30$ MeV/nucleon is required for He^4 breakup, since the final velocity of ejection has been computed to be twice the initial velocity behind the shock. In the models considered by Colgate, conditions favorable to nucleosynthesis of deuterium (proper density, and so on) were achieved for $F_c \approx 10^{-4}$–10^{-3}, which implies that $\epsilon_0 \approx 1$ MeV/nucleon. A number of groups are now investigating shocks in various stellar density configurations. These studies should shed more light on the domain of validity of the above formulas.

The fraction X of the interstellar matter in the galaxy that has been exposed to a shock wave strong enough to break up He^4 nuclei can be roughly estimated as

$$X = F_c T M_0 / \tau M_g$$

where T is the age of the galaxy, M_g the mass of interstellar gas and τ the average time (in years) between supernovae (of the proper type) in the galaxy. If the observed mass fraction of deuterium is to be produced by such shocks, then $X \gtrsim 2 \times 10^{-5}/0.3$, where the 0.3 appears because only about 30% of the matter exposed to the shocks was He^4. This lower limit to X is very conservative because it assumes that all the helium will be transformed into deuterium, and that all the deuterium produced will avoid subsequent destruction by D + D reactions behind the shock or p + D reactions in subsequent stellar processing. With $T \approx 10^{10}$ years and $M_g \approx 10^{11}\ M_\odot$, this requires that the mass of matter ejected with velocities V greater than 8×10^4 km/sec per supernova be given by

$$F_c M_0 \gtrsim 10^{-4} \tau M_\odot$$

Now, Reeves[35] argues that observations of Type II supernovae (believed to be the type most favorable for deuterium production) indicate that an amount of matter of about 0.3 solar mass reaches velocities $V \geq 1.5 \times 10^4$ km/sec (equivalent to $\epsilon = 1$ MeV/nucleon). If equation 1 applies to the matter at higher velocities, then $F_c M_0 \approx 3 \times 10^{-4}$, which would imply $\tau \lesssim 3$ years. This is much less than the observed time of about 30 years or more between supernovae. However, Colgate[33] has argued that it is not yet possible to extract from observations the amount of matter that has reached such high velocities.

D versus the light elements

Richard Epstein, David Arnett, and Schramm[36] have investigated in detail another constraint on the supernova production of deuterium, the simultaneous production of other light nuclides. By comparing the production cross sections for Li, Be and B with that of D, one can see that (as in the case of the galactic cosmic rays) more of these elements are produced relative to D than is observed. For example, the ratio by mass of the production of Li^7, by

$$\alpha + \alpha \longrightarrow Li^7 + p$$

to the production of D, by

$$p + \alpha \longrightarrow D + He^3$$

is about 5×10^{-2}, which compares to an observed ratio of 3×10^{-4}. Of course, variations in the energy spectrum and additional contributions to production through other channels will affect the production rates. The final abundances will also be affected by the rates of destruction, but one cannot allow much destruction of deuterium if one is to account for the total amount observed in the galaxy. Nevertheless, *if the total abundance of Li, Be or B relative to D produced in the shock is greater than the observed ratio, most of the deuterium could not have originated there,* since any subsequent stellar destruction of Li, Be or B would imply even more destruction of D, because of its lower Coulomb barrier.

Epstein and his collaborators[36] have calculated the evolution of the nuclear abundances in matter that is exposed to a shock wave of the type envisaged by Colgate. They employed a network of all important reactions (including spallation effects) involving nuclei from hydrogen to oxygen. Figure 2 presents the abundances they calculated as a function of the energy per nucleon, in the shock, $\frac{1}{2} m_u V^2 \approx 3kT_0$ (where T_0 is the peak ion temperature). Notice that deuterium is produced most rapidly in higher-energy shocks. This is related to the fact that the breakup of He^4 requires more energy than the breakup of carbon, nitrogen or oxygen nuclei. We recall that each shell of mass will be traversed by a different energy shock, so that equation 1 must be used to weight the abundances in figure 2 to give the total abundances; these are shown in Table 3.

Table 3. Production by supernova shock waves

Nucleus	Cosmic abundance (by mass)*	Theoretical abundance in supernova ejecta	Calculated/ observed
D	2.0×10^{-5}	$4.3 \times 10^{-5}\ \epsilon_0^2$	$2.2\ \epsilon_0^2$
He^3/D	1.3	0.32	0.25
Li^6/D	2.5×10^{-5}	1.6×10^{-5}	0.64
Li^7/D	3.6×10^{-4}	3.5×10^{-3}	9.7
Be^9/D	8.2×10^{-6}	2.4×10^{-4}	29
B^{10}/D	3.5×10^{-5} (7.7×10^{-4})	1.4×10^{-4}	4.0 (0.18)
B^{11}/D	1.6×10^{-4} (3.5×10^{-3})	1.9×10^{-2}	120 (5.4)

* These are from reference 16, except for boron (reference 29) and deuterium. Even with the high boron abundances favored by Cameron[16] (in parentheses), too much B^{11} is produced relative to D.

Figure 3 shows the evolution of the abundances and ion temperature in a typical mass shell. Notice that about 10 milliseconds after the shock passes, the ion (and electron) temperature T drops rapidly as enough photons are created to produce a Planck distribution at about 10^7 K. Most of the internal energy then resides in the photons. The rate of ion cooling is one of the uncertainties in Colgate's model; Epstein, Arnett, and Schramm are currently studying the effects of other cooling curves. Notice also that B^{10} and Li^6 are rapidly depleted in this region, while Li^7, Be^9, and B^{11} are not. This depletion is due to the large neutron-capture cross sections of Li^6 and B^{10}. The results shown in figures 2 and 3 are independent of density ρ in the range considered, 10^{-8} to 10^{-5} gram/cm^3.

Table 3 summarizes the total yields of light elements in such a supernova explosion. Note that, since the abundances are all proportional to ϵ_0^2 as indicated by equation 1, the relative abundances are independent of this parameter. It is clear that Li^7, Be^9, and B^{11} are greatly overproduced in such an explosion, by factors of 5 to 30 or more. These results are reasonably certain in view of the fact that most of the key reaction rates have been experimentally determined. For example, the rates in the reaction chain

$$N^{14}(p,\alpha)\ C^{11}\ (e^+,\bar{\nu}_e)\ B^{11}$$

which produces most of the boron-11, are known accurately. It is also of interest that, even in supernovae with few carbon, nitrogen or oxygen nuclei, lithium-7 will still be overproduced by the reaction

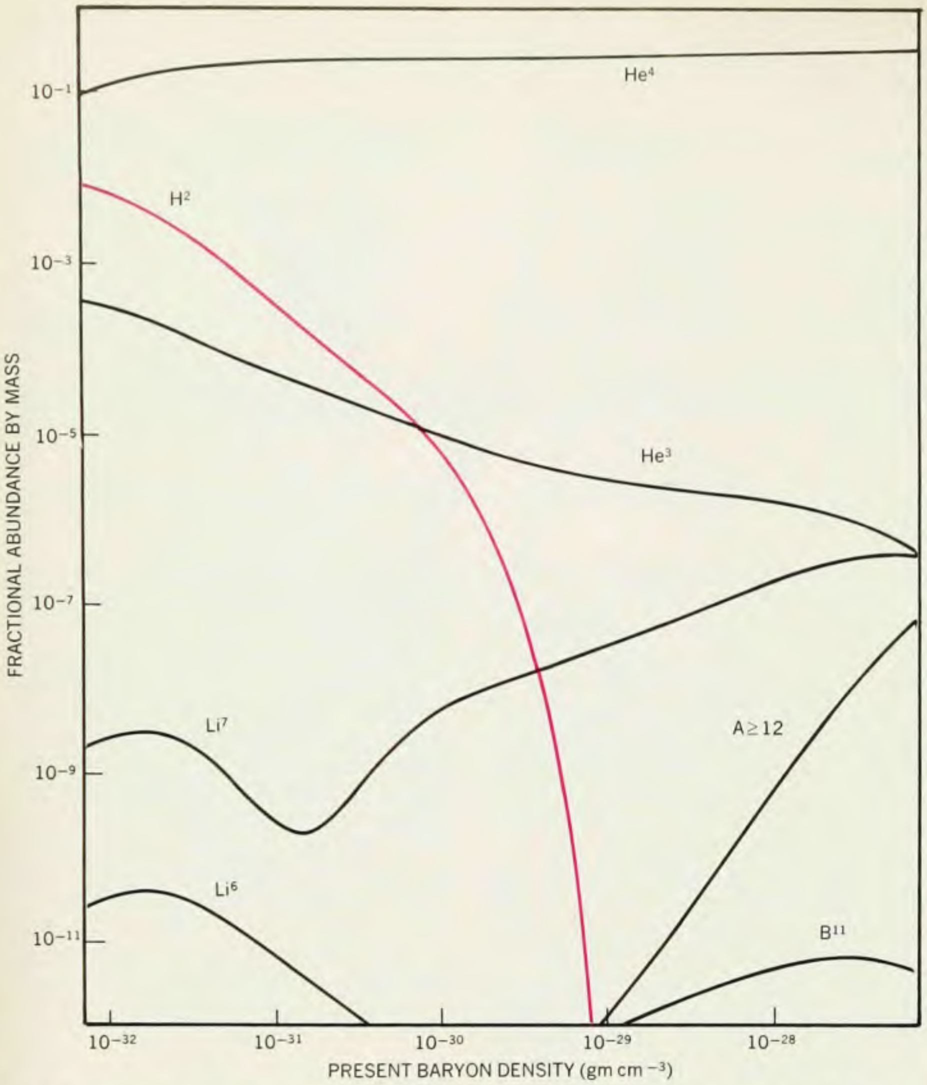
$$\alpha + \alpha \longrightarrow Li^7 + p$$

Thus we conclude that such shock waves are better candidates for the production of Li^7, Be^9, and B^{11} than D. Of course, different shock structures still need to be investigated before significant deuterium production is ruled out, but these results certainly do not engender optimism for this model.

Hoyle and Fowler[34] have considered the alternative possibility that shock-wave production of deuterium takes place in exploding supermassive objects ($M \gtrsim 10^4 M_\odot$). Unfortunately, such objects have not yet been directly observed. Although no detailed calculattions have yet been carried out, the problem of overproduction of other light elements would probably persist also in such objects.

Deuterium from the primeval fireball?

The existence of the microwave background radiation provides strong evidence that the universe has expanded from a state of high temperature and



The dependence of the final cosmic mass fractions of various nuclides, and of all of mass number 12 and above, on the postulated value of the present baryon density, based on the present photon temperature of 2.7 K, is shown here for standard big-bang models. Figure 5

density.[37] As we shall see, however, the density may have been low enough during the epoch of nucleosynthesis ($T \approx 10^9$ K) to permit the survival of deuterium.

The theoretical framework within which cosmological element production will be considered is based upon two fundamental principles:

- The equivalence principle (local validity of special relativity in all free-falling reference frames). This principle has been verified to high accuracy by a variety of experiments.[38]
- The cosmological principle (homogeneity and isotropy of the universe). This principle is supported by the relation between the apparent magnitudes and red shifts of galaxies and their isotropic distribution,[39] the isotropy of the distribution of radio sources[40] and the isotropy of the microwave background radiation itself.[41]

In addition to these principles, the "standard model" of the universe employs the following less firmly established assumptions:

- The fireball temperature was once greater than approximately 10^{11} K.
- Only known particles (γ, e^-, e^+, ν_e, ν_μ, n, p, nuclei; but no quarks, superbaryons, anti-hadrons, etc.) were present during nucleosynthesis.
- All particles (in particular the neutrinos) were nondegenerate.
- The expansion rate is given by the general-relativistic formula, $V^{-1}dV/dt = (24\pi G\rho)^{1/2}$, where V is a comoving volume element and ρ is the total mass-energy density.

Soon after the discovery of the microwave background radiation, detailed calculations revealed that deuterium could be produced in the "big bang."[42] In these and more recent investigations,[43,44] element production in "nonstandard" models of the universe has also been computed. However, we will first discuss nucleosynthesis in the standard model and then mention some effects of departures from its assumptions.

The evolutions of the abundance $X(i)$ of nucleus i and baryon mass density ρ_b in a typical standard model is shown in figure 4. At temperatures above about 10^{10} K, the neutron-proton ratio is held at its equilibrium value (somewhat less than unity) through the weak reactions

$$e^+ + n \rightleftharpoons p + \bar{\nu}_e \text{ and}$$
$$\nu_e + n \rightleftharpoons p + e^-$$

At temperature from 10^{10} K down to 3×10^8 K, the neutron decay rate is still slow compared to the expansion rate $V^{-1}\ dV/dt$. Nucleosynthesis takes place at $T \approx 10^9$ K, when the rate of photodisintegration of deuterium has dropped enough to allow its equilibrium abundance to increase enough to allow, in turn, the buildup of heavier nuclei. At lower temperatures the Coulomb barriers prevent further nucleosynthesis. Since virtually all of the neutrons are used in synthesizing He^4, its final abundance is determined mainly by the precise temperature at which the nucleon weak reactions indicated above "freeze out" of equilibrium, which in turn is determined by the equality of their rate and the expansion rate.

Because the expansion rate is determined by the total density $\rho \gg \rho_b$ at this epoch (although today $\rho \approx \rho_b$), the final helium-4 abundance is approximately independent of the baryon density then. On the other hand, the abundances of the other nuclei do depend upon ρ_b or, more conveniently, on the ratio ρ_b/T^3, which is inversely proportional to the number of photons per baryon, and remains approximately constant throughout the subsequent expansion of the universe. This is the only free parameter in the standard model. Instead of this ratio, it is more convenient to use the equivalent choice of present baryon density, since we know that the present photon temperature is 2.7 K.

The final abundances produced in standard models of the universe are shown in figure 5. The first thing to notice is the fairly constant level of He^4 production claimed, with the helium-4 abundance ranging from 0.20 to 0.30 for a present baryon density ranging from 4×10^{-32} to 4×10^{-28} grams/cm^3. The sensitivity of the helium abundance to the relation between the rate of expansion of the universe and the rate of the weak nucleon reactions results in its abundance being much different in most nonstandard models (with degenerate neutrinos, anisotropy, other theories of gravity, new types of particles, and so on). We thus believe that the fact that the observed universal helium abundance appears to be precisely in this range[43] provides strong evidence for the validity of the standard model, which we hereafter accept. Of course, one still would like to be able to show conclusively that stars could not have produced the observed helium, but its constant level of abundance in other galaxies does favor a cosmological origin.

The next thing to notice is that deuterium survives in the lower-density models of the universe. Allowing for the depletion by subsequent stellar processing, the pregalactic abundance of deuterium must be $X(\mathrm{D}) > 2 \times 10^{-5}$ if it is of cosmological origin. This then leads to the upper limit $\rho_b < 6 \times 10^{-31}$ gram/cm^3 today, independent of the Hubble constant H_0. It can also be seen from figure 5 that this implies the additional pregalactic abundances $X(\mathrm{He}^3) > 1.4 \times 10^{-5}$ and $2 \times 10^{-10} < X(\mathrm{Li}^7) < 3 \times 10^{-9}$, with no appreciable production of other nuclei. It may be significant that the only light nuclei that cannot be produced by the galactic cosmic rays (Table 2) can be produced in the early universe, although the Li^7 production is somewhat below the observed level $X(\mathrm{Li}^7) \approx 6 \times 10^{-9}$. However, Li^7 production may be possible in other sites.[21]

The observable matter in galaxies provides[45] the definite lower limit to the baryon density, $\rho_b > 1.3 \times 10^{-3} \rho_c = 7 \times 10^{-33} (H_0/55)$,[2] where the "critical density" $\rho_c \equiv 3H_0^2/8\pi G = 5.7 \times 10^{-30} (H_0/55)^2$. It is generally believed that the Hubble constant H_0 lies between 50 and 100, $H_0 = 55$ km sec^{-1} Mpc^{-1} being Allan Sandage's present best value.[46] Using more reasonable estimates based on the virial theorem for galactic masses yields[45] a density of matter in the form of galaxies of about $(0.05 \pm 0.01)\ \rho_c \approx 3 \times 10^{-31} (H_0/55)^2$ gram/cm^3. This is certainly consistent with the upper limit on baryon density of 6×10^{-31} gram/cm^3 obtained from the deuterium abundance.

An open universe?

Assuming that the present universe is governed by general relativity with arbitrary cosmological constant Λ, and that its present density ρ_0 is mostly in the form of baryons, one obtains, for its dimensionless curvature,

$$\kappa \equiv k\left(\frac{c}{H_0 R_0}\right)^2 = \frac{3\rho_0}{2\rho_c} - q_0 - 1$$

in terms of the observed quantities ρ_0, ρ_c and the "deceleration parameter" q_0, which represents the rate at which the expansion of the universe is slowing down. If $\rho_0 < 6 \times 10^{-31}$ gram/cm^3 and $H_0 \geq 50$ km sec^{-1} Mpc^{-1}, then

$$\kappa < -0.81 - q_0$$

This implies that the universe is infinite and open ($\kappa < 0$) unless $q_0 < -0.81$; such an open universe eventually contracts if $\Lambda < 0$ and continually expands if $\Lambda \geq 0$. Within two standard deviations, q_0 is positive according to Sandage, assuming $\Lambda = 0$ and negligible evolutionary corrections to the galaxies used.[47] It is known, however, that galactic evolutionary effects could reduce this lower limit on q_0.[48] Nevertheless, if $\Lambda = 0$, then $q_0 = \rho_0/2\rho_c$, implying $\kappa < -0.88$. This result likewise points to an open universe that will expand forever.

We have seen that deuterium observations tell us a lot about the universe: Deuterated molecules tell us about chemical fractionation in the solar system and in chemical processes within dense interstellar clouds. Any observed abundance variations of deuterium in space and time might tell us where it was produced. In fact, searches are now under way for possible deuterium enrichment in supernova remnants. The amount of deuterium tells us about conditions in violent stellar explosions if it is of galactic origin (but see recent work[49] by Tom Weaver and George Chapline); if it is primeval, it tells us about the nature of the universe itself.

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