Deuterium in the Universe

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All the heavy hydrogen in space may have been made in the first 15 minutes after the big bang. Observations leading to estimates of its abundance thus provide evidence on conditions at that time.

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The calculations of modern cosmology lead to the conclusion that the universe originated between 10 and 20 billion years ago. The particular cosmology that seems to have the greatest weight of observational evidence behind it is the "big bang" theory, which posits that all the matter in the universe was compressed into a superdense kernel that exploded and has been expanding ever since. Within the past few years evolving techniques of observation have made it possible to look backward in space and time to what appear to be the first few minutes after the big bang, and to learn about the physical state and early evolution of the universe.

One item of observational evidence in favor of the big-bang theory was the discovery that the universe is permeated uniformly by radiation corresponding to what would be radiated by a theoretically perfect "black body" with a temperature of three degrees Kelvin (degrees Celsius above absolute zero). This radiation is believed to be a remnant of the original big bang. The newest evidence has come to the fore only recently. It is the detection in interstellar space of atoms that may have been formed within the first 15 minutes after the big bang. These atoms are the atoms of deuterium, commonly known as heavy hydrogen.

The big-bang theory stemmed from the discovery by Edwin P. Hubble half a century ago that all other galaxies appear to be receding from ours, and that the most distant galaxies seem to be receding the fastest. The big-bang theory accounts for Hubble's observations by the expansion of the universe, as does the steady-state cosmology advanced by Hermann Bondi and Thomas Gold and independently by Fred Hoyle. The steady-state theory, however, postulates that the universe has always looked the same as it does today, and it requires that hydrogen be continuously created to make up for the decreasing density of the universe caused by its expansion. Most astronomers believe this explanation has been ruled out by the discovery of the three-degree background radiation. A variant big-bang cosmology posits that the universe will stop expanding and then contract. The recent measurements of interstellar deuterium have provided a method for determining whether that will happen or whether the universe will simply go on expanding forever.

The "standard" big-bang theory states that in the first 100 seconds after the initial explosion of the universe only protons, neutrons, electrons, positrons and various types of neutrinos existed and that each particle was independent. As the exploding universe cooled, the protons and neutrons began to combine. Since the nucleus of an atom of "ordinary" hydrogen is simply a proton, the combinations of protons and neutrons were the nuclei of the heavier isotopes of hydrogen and of the other atoms. The simplest compound nucleus is the deuteron, composed of one neutron and one proton, which with a single electron forms an atom of deuterium. The nucleus of the third isotope of hydrogen, tritium, consists of one proton and two neutrons. The combination of two protons and one neutron forms the nucleus of an atom having a quota of two electrons; it is the light isotope of helium. The nucleus of the common isotope of helium has two protons and two neutrons. The nuclei of heavier elements are built up in the same way.

In 1948 Ralph A. Alpher, Hans Bethe and George Gamow first calculated the way in which the nuclei of the lighter elements could have been synthesized in the big bang. In 1957 one of us (Fowler), together with Geoffrey Burbidge, E. Margaret Burbidge and Hoyle, laid out a blueprint showing how both the lighter and the heavier elements could have been built up in the interior of stars. Seven years later Hoyle and Robert J. Tayler calculated that the large amount of helium observed throughout the universe (between 20 and 30 percent of the total mass) could not have been manufactured in ordinary stars. The nuclei require a temperature of 10 billion degrees K. for their synthesis, a temperature that could have been attained only in the big bang, in the explosions of supermassive stars ("little bangs") or in supernovas, the explosions of ordinary stars.

In 1966, after the discovery of the three-degree background radiation, P. J. E. Peebles tried to calculate what the relative abundance of deuterium and helium would have been if those two elements had been formed in the big bang. At the same time Robert V. Wagoner joined Fowler and Hoyle to check whether or not the new data sufficiently changed the outcome of previous calculations enough to allow heavy elements to have been synthesized in the big bang. They found that it was still not possible. Could these elements have been formed in events other than the big bang? Let us deal first with their synthesis in the big bang and then discuss the possible exceptions.

The calculations of Wagoner, Fowler and Hoyle show that there is only one isotope left over that is unique to the big bang. It is deuterium. Although helium would also have been made in the big bang, additional helium has been synthesized since then in stars and cannot now be distinguished from the original helium. Deuterium, however, is only depleted by the processes that go on inside ordinary stars; it is "cooked" into heavier elements by thermonuclear reactions. Therefore whatever deuterium we find now may well have persisted since the origin of the universe. The deuterium would have been formed in the first 1,000 seconds after the big bang, when the rapidly expanding universe had cooled off just enough to allow protons and neutrons to combine. In some sense, then, deuterium may actually allow us to look backward 10 to 20 billion years in time.

In order to use deuterium as a key to gaining a fuller understanding of the big bang, it is necessary to determine how abundant deuterium is with respect to ordinary hydrogen. Ideally we should like the cosmic abundance ratio, if it exists as a meaningful constant, to be uncomplicated by processes inside stars or by the chemical interactions of elements and compounds on planets or on grains of ice or dust in space. The ratio is best measured in the gas between the stars.

The density of the interstellar gas is very low: about one atom per cubic centimeter. The space between the stars is so vast, however, that the total amount of gas is very large. It is well known that almost all this gas is hydrogen. The problem is to find out if any of the hydrogen is deuterium and if so how much.

How can deuterium be observed? In an atom of ordinary hydrogen the single proton and single electron act as though they are spinning like tiny tops. The spin of the electron can be either in the same direction as the spin of the proton or in the opposite direction. If the spins are in the same direction, the atom is in a higher energy state, and the electron spin can flip over so that it is spinning in the opposite direction with respect to the proton. This spin-flip emits a small amount of energy at the radio wavelength of 21 centimeters. Gaseous hydrogen can also absorb energy at this wavelength as well as emit it. The atoms that absorb the energy are thus put into the higher energy state. Although the spin-flip for any one atom is rare, there are enough atoms in the galaxy for the radiation at 21 centimeters to be quite strong.

Deuterium also has a single electron, and the radiation from its spin-flip is at a wavelength of 92 centimeters. Deuterium, however, is much less abundant than ordinary hydrogen. In the water of the earth's oceans there are 6,600 atoms of ordinary hydrogen for every atom of deuterium. The abundance of deuterium in the solid body of the earth could be quite different. Thus the value for the oceans does not necessarily reflect the abundance ratio of deuterium to ordinary hydrogen on the earth, much less the ratio in interstellar space.

Soon after the spectral line of hydrogen at 21 centimeters was discovered, several astronomers began to search for the line of deuterium in interstellar space. The surveys culminated 10 years ago when Sander Weinreb of the National Radio Astronomy Observatory (NRAO) at Green Bank, W.Va., turned the observatory's 85-foot radio telescope to the constellation Cassiopeia to look for the 92-centimeter line in the spectrum of the strong radio source Cassiopeia A. Although Weinreb observed for weeks, he was totally unable to detect deuterium. He stated on the basis of his negative observations that the ratio of deuterium to ordinary hydrogen in that direction appeared to be less than 1 : 13,000, since any larger amount would have been detected. That upper limit is half the ratio of deuterium to ordinary hydrogen on the earth.

Radio astronomy has continued its rapid development since the time of Weinreb's survey, and within the past few years many complex molecules have been detected in the clouds of gas and dust in interstellar space. Most of the molecules have been found at relatively short wavelengths, from about 21 centimeters down to two millimeters. Few spectral lines have been discovered at wavelengths longer than a meter, although the failure has not

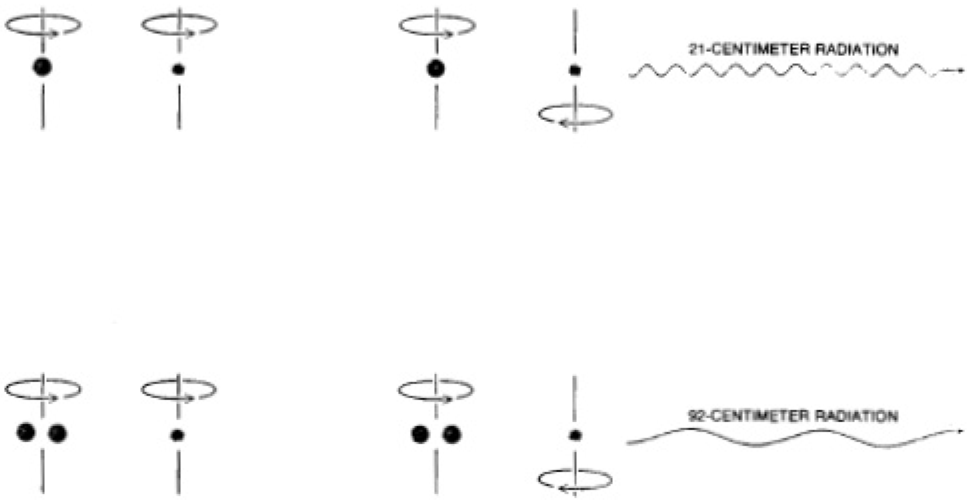


Figure 67 SPIN OF THE ELECTRON flips on rare occasions in an atom of hydrogen or deuterium with the emission of radiation. In the schematic at top left the nucleus and electron in an atom of ordinary hydrogen spin in the same direction. When the electron flips so that it is spinning in the opposite direction (*top right*), radiation is emitted at a wavelength of 21 centimeters. The same kind of spin-flip in the deuterium atom (*bottom drawings*) gives rise to 92-centimeter radiation. When the atoms absorb radiation of same wavelength, the spin of their electron flips back.

been for lack of trying. In 1969 Carl A. Gottlieb, Dale F. Dickinson and one of us (Pasachoff) used the 150-foot radio telescope of the Air Force Cambridge Research Laboratories to search at meter wavelengths for various molecules, some of which included deuterium as a constituent. Two such molecules were the hydroxyl radical (OH), with deuterium in place of ordinary hydrogen, and water, with deuterium in place of one of the two ordinary hydrogens. The search was later continued at the NRAO in collaboration with David Buhl, Patrick Palmer, Lewis E. Snyder and Ben Zuckerman. No molecules were detected.

The chance of finding the faint spectral line of deuterium, or for that matter any other spectral line at such wavelengths, seemed very small. Nevertheless, in conversations in 1970 the authors of this article felt that another attempt should be made. The project would call for many weeks of observing, but it seemed that the 130-foot radio telescope of the Owens Valley Radio Observatory of the California Institute of Technology might be available. Diego A. Cesarsky and Alan T. Moffet of the staff at Owens Valley joined one of us (Pasachoff) in making the observations. In the following discussion of these observations "we" refers to Cesarsky, Moffet and Pasachoff and students from Williams College and Cal Tech who worked with us.

We decided to observe for two weeks at a time because we wanted to analyze the results as we went along. Many problems could have interfered with the investigation. For example, the 92-centimeter line lies in a region of military air-to-ground communications. Although the aircraft transmissions were sometimes bothersome, we were able to remove those time periods from our data.

The first two weeks of observing were in March, 1972. The main direction in which we chose to observe was toward the center of our galaxy. The galactic center, however, is in the southern sky, and at the latitude of the Owens Valley it is above the horizon for only about six hours a day. Since radio telescopes can operate in broad daylight, we were able to observe the galactic center whenever it was above the horizon, to observe in the direction of the Great Nebula in Orion much of the rest of the time and to observe in the direction of Cassiopeia A during any intervening hours. The data from this first observing run looked good, showing that the telescope and the receiving system were working satisfactorily. Furthermore, there was actually a suspicion of a faint absorption line at 92 centimeters.

That summer we had three more observing runs of two weeks each, extending the results of the first run. We concentrated our efforts in the direction of the galactic center. There is more hydrogen in front of that source than in any other part of the sky. We assumed as a working hypothesis that the abundance ratio of deuterium to ordinary hydrogen is constant throughout the universe, so that presumably the greatest total amount of deuterium would lie in the same direction as the greatest total amount of ordinary hydrogen. The galactic center is a strong source of radio waves, and the gas in the 40,000 light-years between it and the earth absorbs some of the radiation at the wavelengths of 21 to 92 centimeters.

Our analysis of the data by computer during that summer and fall strengthened our belief that we were actually observing the absorption line of deuterium. In the summer of 1973 five more weeks of observing by Cesarsky and Pasachoff yielded results that were compatible with the findings in 1972. We attempted to observe over a wider range of wavelengths, but it seemed as though we were now encountering too much outside interference in the wider band. In the narrower range of wavelengths observed in common during both years, the largest absorption fluctuation again corresponded to the spectral line of deuterium at 92 centimeters.

The line is still only barely visible in the data, which show expected random fluctuations (see Figure 68). Adding the results of both years' observations together has slightly improved the ratio of the signal to the noise and the line seems more than three times as strong as the fluctuations. Even if the "line" turns out to be only a particularly large random fluctuation in the data, the magnitude of the surrounding noise places an important upper limit on how strong the absorption could be. From our data that upper limit is one part in 3,000. If the feature we observed is the deuterium line, then the abundance ratio of deuterium to ordinary hydrogen would be between 1:3,000 and 1:50,000.

Curiously the major part of the uncertainty in that range arises not because the absorption line of deuterium is so weak but because the radiation from ordinary hydrogen with which it is compared is so strong. In the distance between the galactic center and the earth there is so much hydrogen that the radio signal is saturated. The result is that one cannot tell exactly how much hydrogen there is in this space, and one can only determine a lower limit.

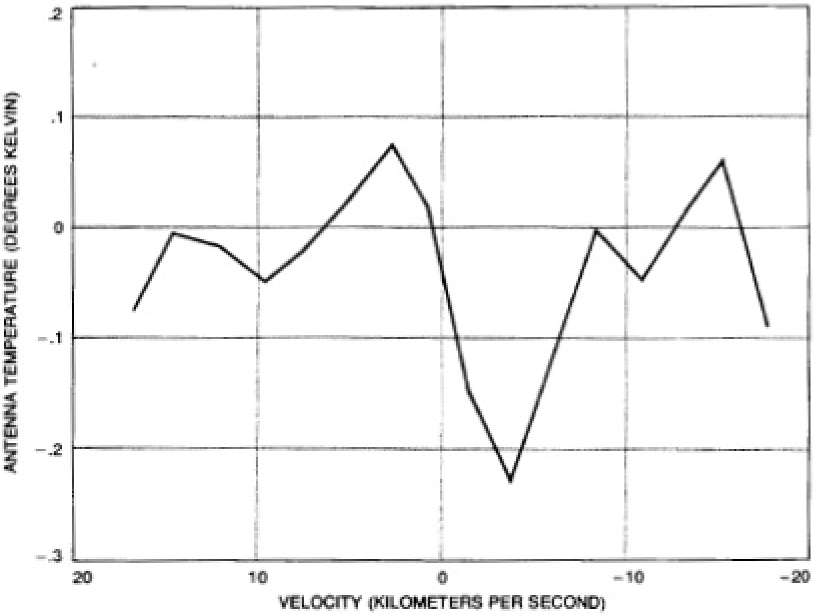


Figure 68 ABSORPTION LINE OF DEUTERIUM shows up as the central dip in observations of the galactic center at a wavelength of 92 centimeters. The dip is shifted in frequency by a small amount, indicating that the gas incorporating the deuterium is moving at a velocity of 3.7 kilometers per second toward the solar system. The spectrum is calibrated in terms of temperature of antenna, equivalent to the energy of radiation received by antenna.

The next step in improving the determination of the abundance ratio of deuterium to ordinary hydrogen is not only confirming the detection of the absorption feature at 92 centimeters but also improving the measurements of the strength of the hydrogen radiation at 21 centimeters.

The gas seems to have the small velocity of 3.7 kilometers per second in our direction. The spectral lines of other gases observed in the direction of the galactic center, notably the hydroxyl radical and formaldehyde (H_2CO), are also Doppler-shifted by an amount that corresponds to the same velocity.

At the same time that we were making our first observations Keith B. Jefferts, Arno A. Penzias and Robert W. Wilson of the Bell Laboratories were observing DCN, that is, the deuterated form of the hydrogen cyanide molecule (HCN). With the 36-foot radio telescope of the NRAO located on Kitt Peak in Arizona, Jefferts, Penzias and Wilson turned their attention to the Kleinmann-Low nebula, a small cloud in the Great Nebula in Orion in which many interstellar molecules have been detected. Within the Kleinmann-Low nebula the DCN molecule was radiating very strong spectral lines at the wavelengths of two millimeters and four millimeters. The observations indicated that the ratio of DCN to HCN was 1:170.

This ratio of DCN to HCN is much higher than the ratio of HDO to H_2O in the earth's oceans. It was immediately realized, however, that if the result was to be understood, certain facts of chemistry would have to be taken into account in addition to the facts of physics. Chemical combinations of the elements follow complicated principles and processes, many of which are unknown. That is particularly true for elements combining on the surface of dust grains in interstellar clouds, which is a leading possibility for the way in which such molecules form. The ratio of deuterium to ordinary hydrogen in interstellar space could very well be quite different from the ratio of DCN to HCN. Calculations show that the difference in the ratios from such chemical fractionation may be on the order of a factor of 600. When the observation of Jefferts,

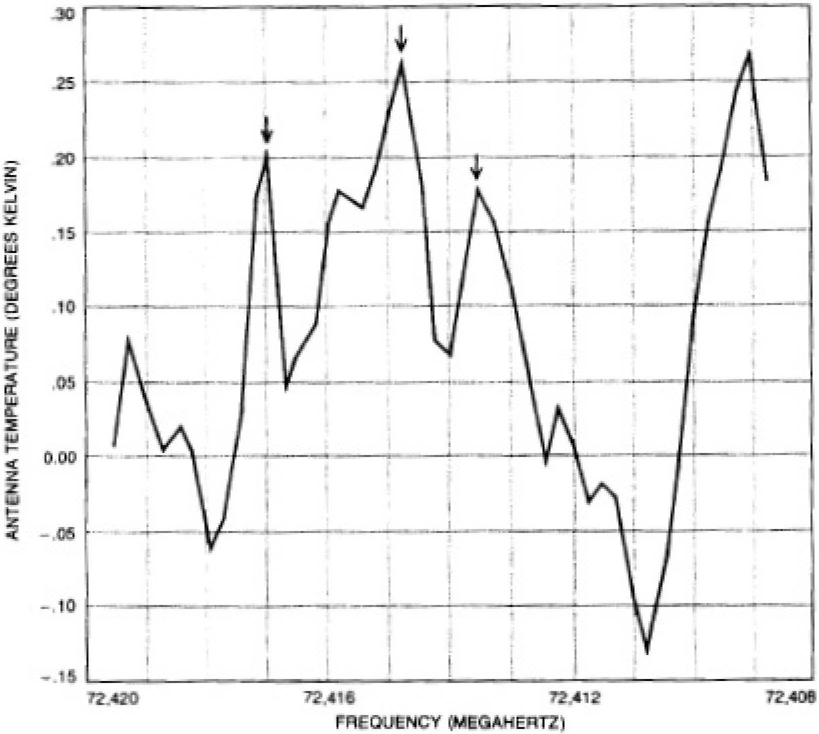


Figure 69 EMISSION LINE OF DEUTERATED HYDROGEN CYANIDE (DCN), which is actually composed of three separate lines (*arrows*), was observed at millimeter wavelengths in Kleinmann-Low nebula in constellation Orion with a 36-foot radio telescope on Kitt Peak.

Penzias and Wilson was adjusted to take the correction factor into account, the ratio of deuterium to ordinary hydrogen in the Kleinmann-Low nebula was found to be 1 : 100,000, just below the range deduced from the observations of Cesarsky, Moffet and Pasachoff. The fact that the ratio of deuterium to hydrogen is indeed substantially lower than the ratio of DCN to HCN has since been confirmed by two independent limits set on the abundance of deuterium by Cesarsky observing at radio wavelengths and by another group observing a transition of deuterium at visible wavelengths.

The abundance ratio of deuterium to ordinary hydrogen has also been determined from space, from the third Orbiting Astronomical Observatory satellite, named *Copernicus*. One experiment, conducted by a group from Princeton University including Lyman Spitzer, Jr., Jerry F. Drake, Edward B. Jenkins, Donald C. Morton, John B. Rogerson, Jr., and Donald G. York, uses a 32-inch telescope to observe spectra at the ultraviolet wavelengths between 950 and 1,450 angstroms and between 1,650 and 3,000 angstroms. The second range includes spectral lines from molecular hydrogen (H_2), detected only once before, in an experiment placed aboard a sounding rocket. Molecular hydrogen had not been detected from the earth's surface because it has no lines in the visible region of the spectrum, and its radiation in the ultraviolet region is absorbed by the atmosphere.

The results from the Princeton experiment aboard *Copernicus* showed that whenever the telescope was pointed toward reddened stars (that is, in directions where the interstellar material in front of stars affects the overall distribution of the energy radiated by the stars by favoring the longer —redder—wavelengths), the spectra revealed that at least 10 percent of the intervening matter was in the form of molecular hydrogen. The same result was obtained with 11 different stars. For a similar number of unreddened stars, however, molecular hydrogen was not detected at all to a limit of one part in 10 million.

Furthermore, the Princeton group measured two lines of HD (deuterated H_2) at wavelengths of 1,054 and 1,066 angstroms. The first results, for nine stars, indicate that the abundance ratio of HD to H_2 is 1:1,000,000. Again the result had to be adjusted by calculations of chemical combinations to yield a corrected ratio of deuterium to ordinary hydrogen. John H. Black and Alexander Dalgarno of the Center for Astrophysics of the Harvard College Observatory and the Smithsonian Astrophysical Observatory have calculated that the ratio of deuterium to ordinary hydrogen is between 1:5,000 and 1:500,000 for the nebula Zeta Ophiuchus.

After these promising measurements had been made Rogerson and York attempted to use the telescope aboard *Copernicus* to observe the Lyman series of transitions of the deuterium atom. These transitions absorb radiation in the ultraviolet region of the spectrum when the electron in the deuterium atom is raised to a higher energy level from the "ground" state. The wavelengths of the transitions are slightly shorter than the wavelengths of the corresponding transitions for the atom of ordinary hydrogen (and were also slightly shorter than the wavelengths for which the experiment was actually designed). The calculation of the ratio of deuterium to ordinary hydrogen from these measurements is straightforward and not subject to the correction factors that must be applied to the molecular observations.

Rogerson and York searched for the transitions in the interstellar gas in front of hot stars of spectral Type B. Such stars have few lines in their own spectra and therefore any absorption lines detected would have been formed in interstellar space between the star and the earth. In the direction of the star Beta Centauri, Rogerson and York were able to measure four lines in the Lyman series for deuterium. The ratio of deuterium to ordinary hydrogen in that direction is 1:70,000, with an error of 15 percent. The work is being continued for other stars. In addition there have been a number of other estimates, as shown in Figure 71. David C. Black of the Ames Research Center of the National Aeronautics

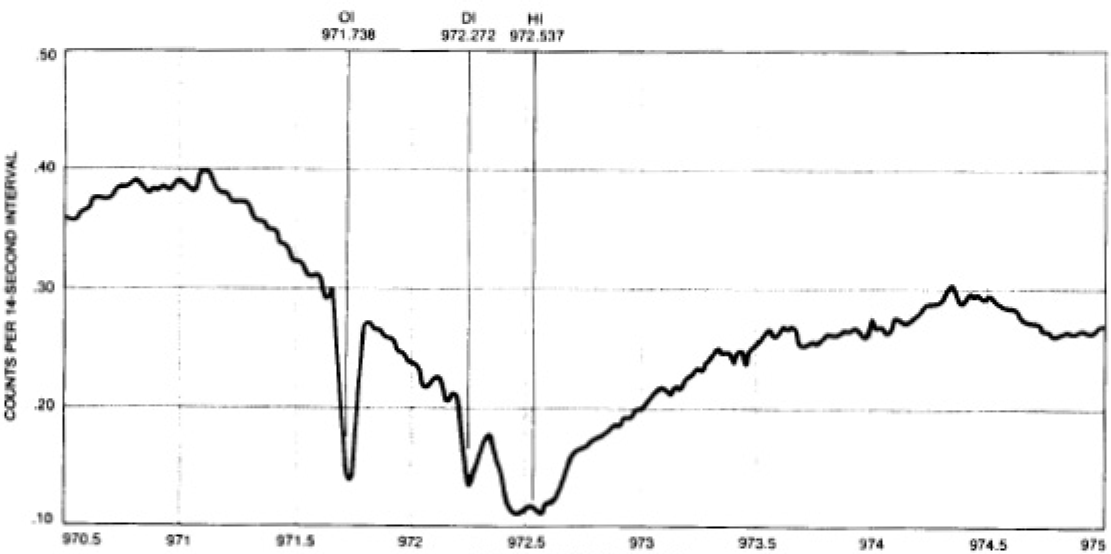


Figure 70 SPECTRUM OF THE STAR BETA CENTAURI shows Lyman-gamma absorption lines for ordinary hydrogen (HI) and deuterium (DI). The lines are from interstellar gas between the star and the solar system. They are superposed on a broad strip Lyman-gamma line from the star (*gentle dip*). A line of oxygen (OI) also happens to be in this region of the spectrum.

and Space Administration deduced the abundance of deuterium in the protosolar nebula from which the sun evolved from measurements of deuterated water (HDO) in meteorites (water in which one deuterium atom replaces one of the two hydrogen atoms in H_2O). Dennis J. Hegyi of the Bartol Research Foundation collaborated with Nathaniel P. Carleton and Wesley A. Traub in their measurements of deuterium in the Great Nebula in Orion at visible wavelengths. Other measurements have been carried out by Mark A. Allen and Richard Crutcher of the California Institute of Technology, Harmon Craig of the University of California at San Diego, G. Boato of the University of Chicago and Nicola Grevesse at the Institute of Astrophysics at Liège in Belgium. "Recombination line" in Figure 71 refers to a spectral line emitted at a radio wavelength when an electron recombining with a deuterium ion to form un-ionized deuterium passes from the 93rd to the 92nd energy level. "Lyman lines" are the spectral lines emitted by a hydrogen or deuterium atom when the electron drops from higher energy states to the ground state. "From ^3He" refers to an abundance of deuterium deduced from the abundance of helium 3.

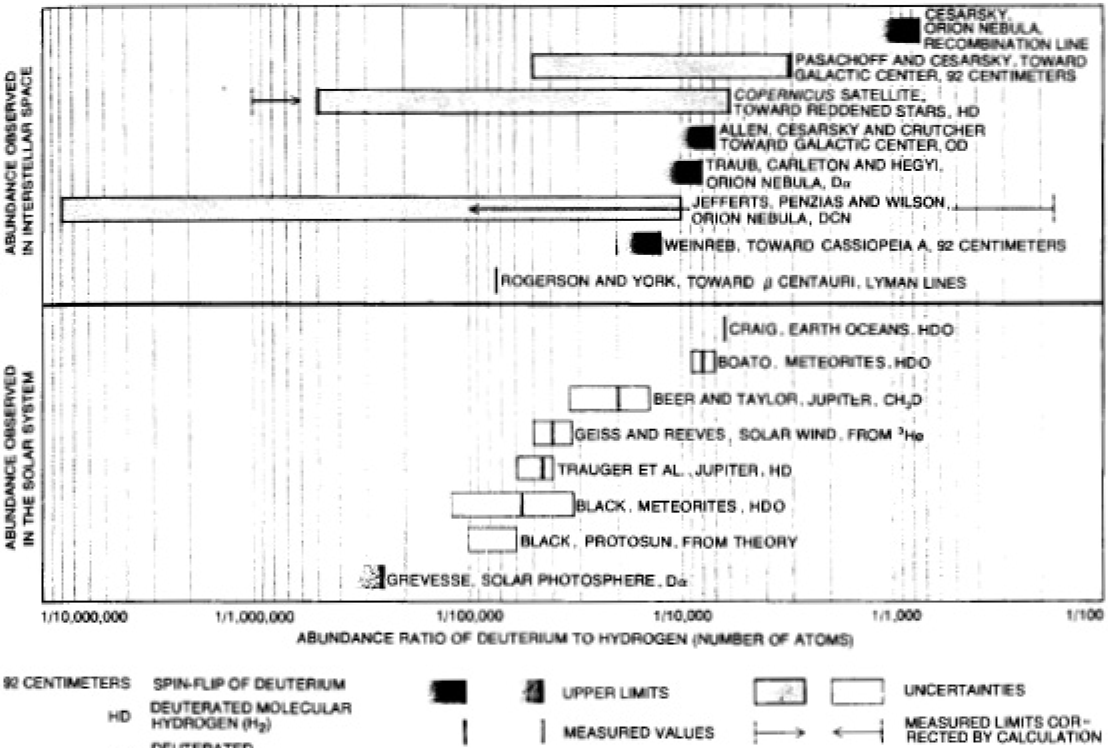
The big-bang theory assumes that the universe is isotropic (that it looks more or less the same in all directions), so that a knowledge of how uniformly deuterium is distributed through space bears on whether or not the big bang is indeed a good model for the origin of the universe. If the abundance of deuterium is found to be nonuniform, for example by comparing the observations from *Copernicus* of nearby stars with our observations toward the galactic center, then either the big bang is not a good model or the deuterium was formed in some way other than the big bang.

In order for the measurements of deuterium to be significant in cosmological calculations, the measurements must reflect a general cosmic abundance and not simply local variations. For this reason it is difficult to interpret the abundance of deuterium in the solar system in terms of a big-bang origin. That abundance should nonetheless be discussed briefly if only because deuterium had not been detected elsewhere in the solar system until last year.

Some deuterium has been found in the water content of carbonaceous meteorites. Until the Apollo astronauts landed on the moon, meteorites were the only samples of matter from space. One of the Apollo experiments was designed to capture ionized atoms from the solar wind: the flux of ions expelled from the sun. The astronauts caught the ions in a "window shade" of aluminum foil they unrolled on the moon. The foil was then brought back to earth for analysis. Johannes Geiss of the University of Bern and Hubert Reeves of the Nuclear Research Center at Saclay and the Institute of Astrophysics in Paris made deductions about the abundance of deuterium from the light isotope helium 3 that had been found in the foil. It is known that the sun has transformed into helium 3 most of the deuterium that was present in the primordial solar nebula, the cloud of dust and gas out of which the sun formed. Therefore the amount of helium 3 in the foil directly reflects an upper limit for the amount of deuterium that could have been present in the solar nebula. Geiss and Reeves have calculated that the abundance ratio of deuterium to ordinary hydrogen in the solar nebula was 1:40,000.

It is also possible that the deuterium in the material from which the planets were made was not transformed into helium 3 as the protosun materialized out of the solar nebula. In March, 1972, Reinhard Beer of the Jet Propulsion Laboratory of the California Institute of Technology and his collaborators reported that they had detected CH_3D, a deuterated form of methane (CH_4), in the spectrum of Jupiter at infrared wavelengths. Beer and Frederic W. Taylor calculated the molecular-correction factors and found that the abundance ratio of deuterium to ordinary hydrogen in Jupiter was between 1:13,000 and 1:35,000, depending on certain assumptions about the structure of the planet's atmosphere.

Although the interpretation of results from such a relatively complicated molecule as CH_3D is very uncertain, the calculations seem to show a clear discrepancy with the value of 1:6,600 found on the earth. Within the past year John T. Trauger and Frederick L. Roesler of the University of Wisconsin and Nathaniel P. Carleton and Wesley A. Traub of the Center for Astrophysics have detected three lines of deuterated molecular hydrogen (HD) on Jupiter in the near-infrared region of the spectrum. From their observations they calculate a ratio of deuterium to ordinary hydrogen of 1:48,000, with a possible error of 20 percent. The discrepancy between the values on the earth and those on Jupiter might be due to the fact that the ratio of heavy water (HDO) to ordinary water (H_2O) on the earth could be enhanced over the ratio of deuterium to



HD DEUTERATED MOLECULAR HYDROGEN (H_2)

OD DEUTERATED HYDROXYL (OH)

Dα LYMAN-ALPHA LINE OF DEUTERIUM

DCN DEUTERATED HYDROGEN CYANIDE (HCN)

HDO DEUTERATED WATER (H_2O)

CH_3D DEUTERATED METHANE (CH_4)

Figure 71 ABUNDANCE OF DEUTERIUM IN THE UNIVERSE as measured both in interstellar space (*black*) and in the solar system (*color*) is shown with respect to the abundance of ordinary hydrogen. The names of the investigators, the region or direction observed and the form of deuterium detected are listed in that order.

ordinary hydrogen by some chemical fractionation process.

A most unusual observation of deuterium was made two years ago. A group of workers from the University of New Hampshire were observing the sun during the large solar flares of August, 1972, with a gamma ray instrument aboard Orbiting Solar Observatory 7. During the particularly large flare of August 7 they detected a peak in the gamma ray spectrum corresponding to the energy that would have been released by the formation of deuterons. That peak meant deuterium was being synthesized on the surface of the sun. This event, however, is probably unrelated to the total cosmic abundance of deuterium. The amount of deuterium formed in this way is small, and it may well be quickly consumed by further nuclear processes on the sun before it can be expelled into space.

The results of the observations of deuterium up to 1974 are summarized in Figure 71. What do these indications of the amount of deuterium in interstellar space tell us about the early universe? One can link the ratio of deuterium to ordinary hydrogen to the big bang by theoretical calculations. For this purpose we shall adopt the standard model of the big bang developed by Wagoner, Fowler and Hoyle, which accepts three basic assumptions about the universe today: first, the universe is homogeneous and isotropic; second, the principle of equivalence must hold, that is, a gravitational field cannot be distinguished from an acceleration (a principle fundamental to the theory of relativity); third, the three-degree background radiation was indeed generated by the big bang. The model also makes several other assumptions. The baryon number must be positive, that is, the amount of antimatter is not equal to the amount of matter, ruling out theories to the contrary. The lepton number is small, that is, the flux of neutrinos does not overwhelm the amount of radiation. The general theory of relativity provides the correct theory of gravitation. Lastly, only the kinds of subatomic particles that we now know about are present; there are no new ones.

In the standard model it happens that the amount of deuterium formed just after the big bang is sensitive to the density of the universe at that time. If the density were relatively high in the first few seconds after the big bang, the deuterium just formed would have been quickly cooked into helium and the end result would be less deuterium. Conversely, if the universe was less dense, the end result would have been more deuterium (see Figure 72). Thus from the measured value of the deuterium in the universe today it is possible to find the density of the universe at the time that the elements were first synthesized. Knowing the density of the universe then and the rate of expansion now, it is possible to calculate what the density of the universe is at present. The density we deduce from our observations is of the order of 10^{-31} gram per cubic centimeter. That density is not enough to "close" the universe, which will thus continue to expand indefinitely. Therefore knowing the universe's present density enables us to draw conclusions about its present state and eventual future.

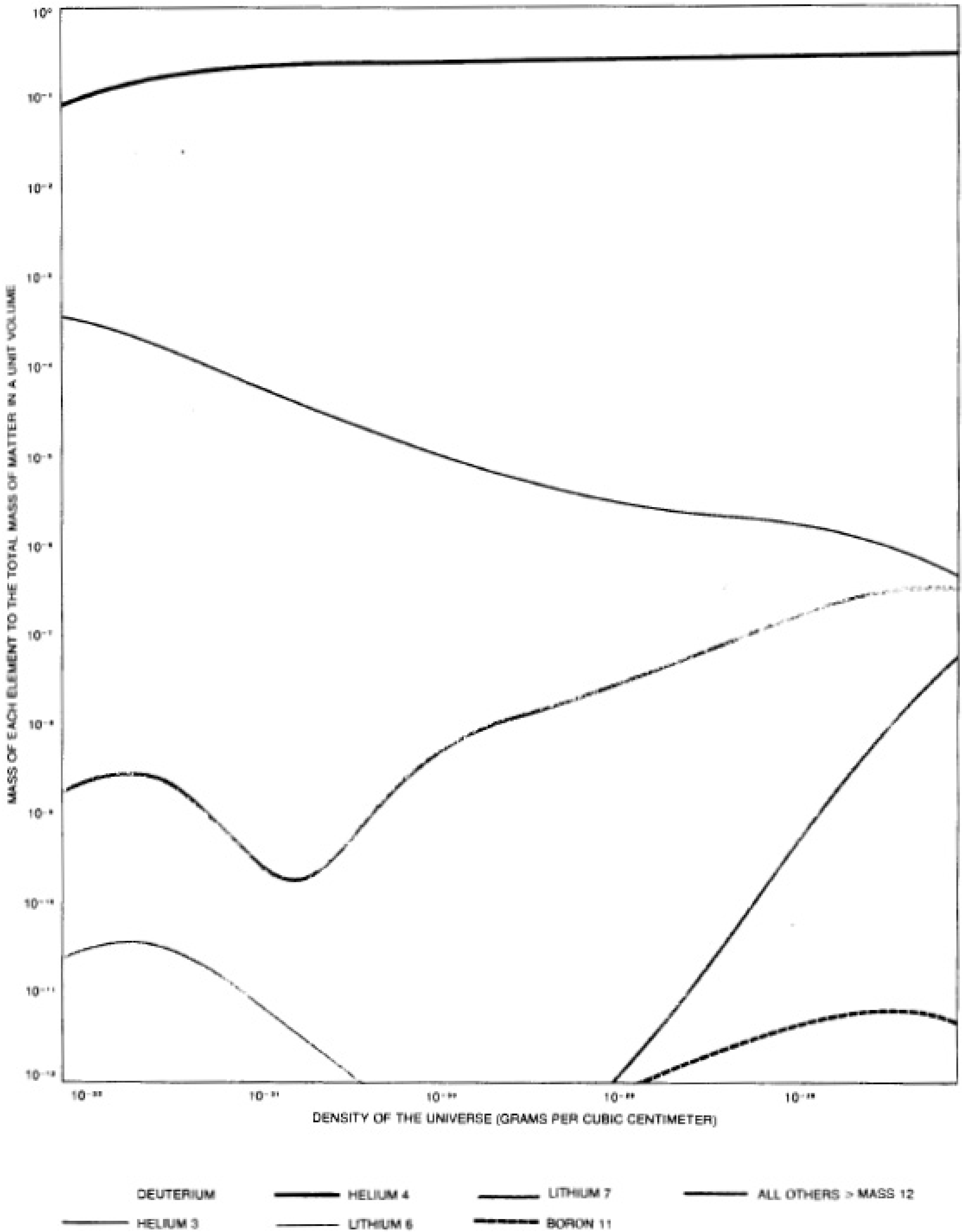
There are two other ways to measure the density of the universe. The first entails simply adding up the masses of everything that can be observed (stars, galaxies and so forth) and dividing the total mass in a given unit volume by that volume. The most recent work along this line has been done by Stuart L. Shapiro of Princeton. His results depend somewhat on the value accepted for the Hubble constant, that is, on the rate at which the universe is expanding. The value of the Hubble constant is currently a topic of debate in some circles. The traditional value is 75 kilometers per second per megaparsec, which corresponds to a density of 10^{-31} gram per cubic centimeter. (One megaparsec is 3.3 million light-years.) A newer value measured by Allan R. Sandage of the Hale Observations and Gustav Tammann of the University of Basel is 55 kilometers per second per megaparsec, which yields three-fourths the density of the former value.

The second method of measuring the density of the universe considers the dynamics of interactions of clusters of galaxies; it predicts a density that is substantially higher than the value obtained by the first method. Both values for the density could be correct if there is a substantial amount of invisible material in the universe. This "missing mass" could be in the form of molecular hydrogen in the intergalactic material, although the measurements from the *Copernicus* satellite seem to indicate that there is not enough molecular hydrogen to account for it. Alternatively, the mass could be in the form of the enigmatic black holes. The observed value for the abundance of deuterium in the universe can place an independent limit on how much invisible matter there could be.

The amount of missing mass in the universe touches on a major question in cosmology: Will the universe go on expanding forever, or is there enough matter in it for mutual gravitational attraction to eventually reverse the expansion? In cosmological terms, is the amount of missing mass large enough to "close" the universe? There is a parameter q_0 that is used in cosmological equations. It is inversely proportional to the Hubble constant, and it represents the rate at which the expansion of the universe is slowing down. If q_0 equals 0, the expansion is not slowing down and the universe is open. If q_0 equals 1, then the universe is closed and will eventually collapse on itself. The dividing line between an open universe and a closed universe is a q_0 of ½. In the steady-state model of the universe q_0 is -1.

Sandage has published a "formal" value for q_0 of $.96 \pm .4$, which would mean that the expansion is slowing down and the universe is closed. His value is based on direct observation of the distant galaxies. The uncertainty in the value, however, means that a q_0 of ½ is not ruled out; $.96 - .4$ is .56, or

Figure 72 "STANDARD" MODEL of the big-bang theory of the origin of the universe predicts an abundance of deuterium that is very sensitive to the postulated density of the universe at the time it originated, as is shown in this diagram devised by Wagoner. The cosmic abundance of a number of other light elements are also given.


MASS OF EACH ELEMENT TO THE TOTAL MASS OF MATTER IN A UNIT VOLUME
DENSITY OF THE UNIVERSE (GRAMS PER CUBIC CENTIMETER)
DEUTERIUM
HELIUM 4
LITHIUM 7
ALL OTHERS > MASS 12
HELIUM 3
LITHIUM 6
BORON 11

virtually ½. On that basis the universe would be open. If the deuterium originated in the big bang with an abundance ratio of the levels now being detected, then q_0 is less than .1 and the universe would definitely be open. It is interesting that according to Wagoner's calculations that is the case for the standard model. There are other cosmological methods of assessing q_0 that also yield low values for the density.

There are several ways to get around the possible disagreement between Sandage's value of q_0 from observations of the distant galaxies and Wagoner's value of q_0 from measurements of the abundance of deuterium. Beatrice Tinsley of the University of Texas has hypothesized that because galaxies evolve over a period of time, an observed value of q_0 equal to 1 could mean that the real value of q_0 is 0. The essential point of her argument is that as we look deeper into space we are also looking backward in time, and that the average brightness of galaxies long ago may be quite different from what it is today. Such a fact would distort the scale of distances, which is based on galaxies having a unique average brightness, and thus the value of q_0 would also be distorted. Tinsley's proposal is a controversial one. Sandage has shown that in order for it to account for the discrepancy between his observations and Wagoner's calculations, the galaxies would have to be decreasing in brightness by about .1 magnitude per billion years, which is very fast according to many theories of the evolution of galaxies.

Another way to resolve the disagreement would be to accept the notion that significant amounts of deuterium were formed after the big bang. Recently one of us (Fowler) and Hoyle have calculated that deuterium could have formed in space by a spallation reaction: if a shock wave could inject helium nuclei into an ionized gas composed mainly of hydrogen, deuterium could be knocked out of the helium nuclei by the force of their impact on the nuclei of ordinary hydrogen. Alternatively, if only a neutron were knocked out of the helium nucleus, the neutron could combine with a proton in the surrounding gas to form a deuteron. Deuterium that came about in this way would not readily break up again; since the temperature of the gas would be low, the amount of energy in it would not be large enough to cause the nuclei to dissociate. Exactly how important such a spallation process would be on the galactic scale remains to be seen. Possibly the process might enhance the ratio of deuterium to ordinary hydrogen in certain local regions such as in the Orion nebula and not in others such as the galactic center.

Another mechanism for producing deuterium apart from the big bang has been proposed by Stirling A. Colgate of the New Mexico Institute of Mining and Technology. The observed deuterium could have been synthesized if 3 percent of the mass of the galaxy had at some time been recycled in supernovas. Deuterium could also have been synthesized in supermassive stars, as was suggested by Fowler and Hoyle. Accepting the hypothesis that deuterium was formed apart from the big bang would probably require a number of significant changes in our views of the relative importance of such phenomena as supernovas in galaxies.

Cosmological problems never seem to admit of easy solutions. With the current observational and theoretical work on deuterium moving ahead so rapidly, however, new lines of reasoning and inquiry are opening up for tackling the most basic questions of the universe.

POSTSCRIPT

In 1974, when our article appeared, the time at which deuterium was formed (three minutes or so after the big bang) was considered early in the universe. Our present understanding of the universe has been pushed so that we talk of times 10^{37} times earlier than the time of deuterium formation.

We observed deuterium because, uniquely, no stellar processes produce deuterium when they form other elements. While many theoretical and observational developments have modified the framework of observations, none has changed the idea that the deuterium abundance can reveal the density of baryons in the universe.

We wrote our article after we had reported a possible detection of deuterium from its fundamental spin-flip line, while others had seen it in hard-to-interpret data from molecules and ultraviolet observations in interstellar space. We had made our observations over many months with a Caltech radio telescope. Our attempt to extend these observations with the Parkes radio telescope in Australia was unsuccessful because we needed extraordinary stability, which was not then available with some of their associated equipment. Subsequently, a group in India reached roughly our sensitivity at the spin-flip wavelength. Their spectra showed no deuterium line, but their beam had a different shape from ours and may not have looked at the same region of space.

The molecular observations continued partially mapping the distribution of deuterium-bearing molecules throughout our galaxy. These observations revealed apparent variations in the deuterium abundance, but the correction factors to give the deuterium-to-hydrogen ratio were too large to allow the density of the universe to be reliably calculated.

The largest observational effort has been to study the deuterium component in Lyman spectral lines taken with the *Copernicus* satellite. The first observations seemed to give 1.4×10^{-5} for the deuterium-to-hydrogen ratio and perhaps solve the problem. Indeed, the possibility that the deuterium: hydrogen ratio was then known may well have prevented us from getting the telescope time we needed to continue our radio work. Years of interpretation of *Copernicus* results followed, studying a dozen stars within 1 kiloparsec (about 3,000 light years) of the sun. Eventually apparent variations in the ratio were found from place to place, even within this small region of the galaxy. By 1983 some of the ratios measured with *Copernicus* had fluctuated from hour to hour, impossible for cosmic deuterium. It turned out that only a narrow band around the expected deuterium wavelengths had been measured in some cases and that this was contaminated by Doppler-shifted hydrogen for a few stars. It took several years before it was found that the values for most of the stars were not contaminated.

Deuterium observations have also been made from the International Ultraviolet Explorer spacecraft, though its spectrograph does not have the spectral resolution of the now defunct *Copernicus*. The latest ultraviolet observations, mainly from *Copernicus*, indicate variations of two from place to place in local regions of our galaxy. Thus, we must continue to observe deuterium all the way to the galactic center, some ten times further away.

One of our limitations had been the size of our beam at the 92-centimeter wavelength that results from the deuterium spin-flip. The availability of synthesis telescopes held out hope for working with a narrower effective beam. In early 1987 receivers at the proper frequency had been installed on 16 of the radio telescopes at the Very Large Array (VLA) of the National Radio Astronomy Observatory, located west of Socorro, New Mexico. An array of this type is best suited for finding enhancements of deuterium in small regions, and K. Anantharanaiah, Donald A. Lubowich and I had a test run of one night to search for such enhancements in the direction of the center of our galaxy. Our preliminary result is that no enhancement by a factor of 100 exists. Also in 1987, a negative result was reported for a search for emission from deuterium in the opposite direction from earth, that of the anticenter of our galaxy. Further, astronomers in the Netherlands have begun deuterium observations with an array of radio telescopes there.

Other observations continue to extend deuterium studies. Deuterium molecules have been found in the atmospheres of Jupiter, Saturn, Uranus and Saturn's moon Titan, though the chemical corrections to the pure deuterium-to-hydrogen ratio are too uncertain to allow cosmological interpretation. A current conclusion is that some of this deuterium came from the protosolar nebula.

The theoretical density of the universe evaluated using the deuterium abundance data has not drastically changed since our article. It has, though, incorporated limits on the number of neutrino types in the universe.

The current interstellar deuterium values indicate that the density of baryons is less than 1/10 of that needed to "close" the universe. How does this square with the prediction of the inflationary universe theory that has the universe on the boundary between being open and closed? If we accept both the inflationary universe and the baryon density from deuterium, we need nonbaryonic matter to provide the additional 90 percent of the mass. Candidates for such nonbaryonic dark matter abound, as discussed in Chapter 1, "Dark Matter in the Universe," by Lawrence M. Krauss. Further observation of deuterium would be useful in evaluating the situation. And we must follow the new theoretical studies of deuterium in an inhomogeneous universe that may explain the observed amount of deuterium at different densities than previously thought.