DEUTERIUM IN THE UNIVERSE

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.

by Jay M. Pasachoff and William A. Fowler

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 that which 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 within the past two years. 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 50 years 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

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 relative yield of the lighter elements that could have been synthesized in the big bang. In 1957 one of us (Fowler) together with Geoffrey Burbidge, Sr., 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. Taylor 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 supernovae with masses of 10 or more solars, in the explosions of massive 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.
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 or 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.

Radio wavelengths for absorption from interstellar deuterium. Stellar center is in the constellation Sagittarius, just above host of stars to right of center. Band dark object is secondary mirror of astronomical camera. Three linear forms are mirror supports.
How can absorption be observed? In the case 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 or in the opposite direction of the spin of the proton or in any intermediate 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 in the form of radio waves. The hydrogen atom, being so simple, can absorb and emit only a few specific radio frequencies.

Doppler effect occurs in a similar way. The frequency or wavelength of the radiation is reduced when the atom is moving away and increased when it is moving closer to the observer. The half of the hydrogen atom or entehron is in ordinary hydrogen, the upper state of the entehron is in deuterium. The entehrons absorb a single electron in the high state of the entehron. The electron in the high state of the entehron can be quite different and thus the value for the deuterium does not necessarily reflect the absolute value of deuterium, which is very different.

The measurement of radio waves from the earth can be done in different ways. Some of the simplest methods are to use a radio telescope to look for the 21-centimeter line in the spectrum. Another method is to use a radio telescope to look for the 3-mm line in the spectrum. The noise level of the radio telescope is much lower than the noise level of the radio telescope. The noise level of the radio telescope is much lower than the noise level of the radio telescope. The noise level of the radio telescope is much lower than the noise level of the radio telescope. The noise level of the radio telescope is much lower than the noise level of the radio telescope.
of the first star. We con-
ized that the universe was not
exists a strong source of radio
waves at the wavelength of 21
centimeters.

Our analysis of the data by computer
during the summer and fall strength-
ened our belief that we were actually ob-
serving the absorption line of deuterium.

In the summer of 1972 we more weeks
of observing by Ceranisky and Pasachoff
yielded results that were compatible
with the findings in 1971. We attempted to
observe over a wider range of wave-
lengths, but it seemed as though we were
now encountering too much outside the
temperature in the outer band. In the var-
cover range of wavelengths observed in
common during both years, the largest
absorption fluctuations again corresponded
to the spectral line of deuterium at 92
centimeters.

The line is still only barely visible in the
data, which show expected ran-
dom fluctuations [see top illustration on
page 113]. Adding the results of both
years' observations together has slightly
improved the ratio of the signal to the
noise and the line appears more than three
times as strong as the fluctuation. Even if
the line turns out to be only a par-
ticularly 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 1,000. If the feature we observed
is the deuterium line, then the abso-
dance ratio of deuterium to ordinary
hydrogen is less than this.
In addition to the facts of physics, electrical considerations of the elements complicated principles and premises of which are unknown. That particularly true for elements composed of the surface of dust grains in distant clouds, which is a leading idea for the way in which such dust form. The ratio of deuterium to hydrogen is interesting, because the ratio of DCN to HCN has been found to be quite different from those of HCN to HCN. Calculations show that the differences in the direct chemical constitution of the 

$\text{H}_2$ $\text{O}$ molecule to ordinary hydrogen in the form of Liquid $\text{O}_2$ and Helium was found to be $10,000$, but below the range and from the observations of Cease and Passchier. The fact that the ratio of deuterium to hydrogen is substantially lower than the ratio of $\text{H}_2$ to $\text{H}_2$, has been used by two independent lines to determine the abundance of deuterium by observing at radio wavelengths. A further group observing the transition of deuterium in the infrared wavelengths, the abundance ratio of deuterium to hydrogen has also been determined from space, the third frequency was that of the Astronomical Observatory satellite Vela X-3. Conducted by a group from the University including Lyman S. Jr., Joyce F. Drake, Edward B. Jr., Donald C. Morton, John B., and Donald G. York, using a telescope to observe spectra at radio wavelengths between 850 megahertz and between 1,250 megahertz. The second range as spectral lines from molecular deuterium. It detected only once before experiment placed aboard a rocket. Molecular hydrogen had been detected from the earth's orbit, because it has no lines to the region of the spectrum, and its size in the ultraviolet region is 1.2 million kilometers per second. The results from the experiments showed that the telescope was pointed towards stars that are, in distances, the interstellar material in stars affects the overall distribution of the energy radiated by the stars where the longer-wavelength values of the spectra revealed that at the Phases of the intervening materia

\text{AMS} \text{ION LINE OF DEUTERIUM shows up at the central dip in observations of the galactic center at a wavelength of 82 centimeters. The observations were made with the 130-foot radio telescope at the Owens Valley Radiotelescope in California. The curve is the sum of results from observations made in 1940 and 1951. The dip is shifted in frequency by a small amount, indicating that the gas separating the deuterium is moving at a velocity of 3.3 kilometers per second toward the solar system. Spectrum is calibrated in terms of temperature of antenna, equivalent to energy of radiation received by antenna.}

\text{EMISSION LINE OF DEUTERATED HYDROGEN CYCLIDE (DCN), which is actually composed of three separate lines, was observed by Keith B. Jefferts, Avino A. Perlmutter and Robert W. Wilson at the Bell Telephone Laboratories at millimeter wavelength. With the 60-foot radio telescope of the National Radio Astronomy Observatory on Kitt Peak in Arizona. The molecule was detected in Kleinmann-Low nebula in constellation Orion.}
Spectrum of the star Beta Centauri is in the ultraviolet region from Lyman-alpha absorption lines for ordinary hydrogen (HI) and deuterium (D). The lines are from the interstellar medium between the stars and the solar system and they are superposed on a broad Lyman-alpha line from the star itself. This suggests that the Lyman-alpha line is not present in the spectrum of the star, but instead is due to the absorption of nearby stars with our observer toward the galactic center. When viewed from the Lyman-alpha line, the star appears to be a composite of two stars, one hotter and bluer than the other. In order for the measurements of these stars to be significant in cosmology, it is essential to have a spectrally pure absorption line or group of spectral lines. Furthermore, it is important to have a spectrally pure line or group of spectral lines that are well-known in the laboratory. In the case of the beta Centauri star, observations have been made to confirm the identification of the Lyman-alpha line and the deuterium line. The experiments have been conducted in laboratories and have yielded consistent results. The observations have been made with a spectrometer that is designed to measure the intensity of the Lyman-alpha line and the deuterium line. The results have been consistent with the predictions of the model.
KLEINMANN-LOW NEBULA is embedded in Great Nebula in Orion, location which is indicated by contours, is rich in many molecules, including deuteron hydrogen cyanide.
of the universe at that time, if the gas were relatively high in the first seconds after the big bang. But just formed would have been truly cool into helium and the next would be less deuterium. Con- conveniently, the universe was less dense, and results would have been more promising. [see illustration in the oppo- site page.] Thus from the measured density in the universe today it is possible to find the density of the uni- verse at the time that the elements were synthesized. Knowing the density the universe than and the rate of ex- pansion, it is possible to calculate at the density of the universe is at zero. The density we deduce from observations is more than 100 times the density of the universe at that time that the elements were synthesized. Therefore knowing the uni- verse's present density enables us to make conclusions about its present-state evolution.

In addition to the standard model of big bang, there is a very speculative hypothesis called the statistical-bootstrap model, advanced by Robert D. Ellis of the University of Chicago, C. Frasch of Cal Tech and then Nahm of the University of Hamburg, that assumes that all cosmic microwave background is approximately the same as ordinary baryons, but mass is a numerical factor. At that point the force of gravity becomes competitive with the natural forces that govern the interaction of matter and particles. The statistical-bootstrap model assumes that there are many elementary fields that have not yet been observed that the energies required to make certain be attained in the laboratory. This model also assumes that the governing the existence of such fields, which have been determined by laboratory for particles with to obtain mass at an ordinary baryonic mass for a further factor in 10^{15}. In one sense this new hy- per, in which there are many fields, is a reversion to the dual theory, which assumes that in none. This is, in fact, a situation in favor one theory over the other.

The statistical-bootstrap model turns out to be accurate, there will be more con- firming for cosmology. First, no galaxy would have been formed in the early universe because so many particles would have been available for a full year after the big bang, and by that time the density of the universe would have been too low for helium to be syn- thetized. Wagoner has calculated the effect of the statistical-bootstrap model on the formation of deuterium. Contrary to the prediction of the standard model, the statistical-bootstrap model predicts that a less dense universe would result in a lower abundance of deuterium [see illustration above].

There are two other ways to measure the density of the universe. The first en- tails simply adding up the masses of every- thing that can be observed (stars, Planck, 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 values 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 observational value is 10 to 100 km per second per megaparsec, which corresponds to a density of 10^{-27} grams per cubic centimeter. [One megaparsec is 3.3 million light-years.] A lower value was obtained by Allan B. Sandage of the Hale Observatories and Cecilia Tam- ma of the University of Basel is 35 kilometers per second per megaparsec, which yields three-thirds the density of the former value.

The second method of measuring the density of the universe involves the dynamics of interactions of clusters of galaxies; it predicts a density that is substi- tutionally higher than the value obtained by the first method. Both values for the density could be correct if there is a sub- stantial amount of invisible matter in the universe. This "missing mass" could be in the form of molecular hydrogen in the intergalactic material, although the measurements from the Copernicus-
it's seen to indicate that there is not enough molecular hydrogen to account for $\alpha$, the mass could be in the form of the ultimate black holes. The observed value for the abundance of deuterium in the universe can place an independent limit on how much invariable matter there would be.

The amount of ordinary mass in the universe becomes a major question in cosmology. With the universe expanding, the mass could be in the form of the ultimate black holes. The observed value for the abundance of deuterium in the universe can place an independent limit on how much invariable matter there would be.

Hubble's constant is the parameter in this model which is needed to scale the universe. It is inversely proportional to the Hubble constant, and it represents the rate at which the universe is expanding. If $\alpha$, equals 0, the expansion is not slowing down, and the universe is open. If $\alpha$, equals 1, the universe is closed, and eventually collapses under its own weight. The division line between a closed universe and a closed universe is $\alpha$, of 1/2. In the steady-state model of the universe, $\alpha$, = 1.

Sandage has published a "best" value for $\alpha$, of 0.36 ± 0.04, 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 $\alpha$, of 1/2 is not ruled out. At $\alpha$, = 0.36 ± 0.04, in virtually 2/3. On this 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 $\alpha$, less than 1/2 and the universe would definitely be open. It is interesting that according to Weygandt's calculations that the case for both the standard model and the statistical bootstrap model are similar. There are other cosmological methods of measuring $\alpha$, that yield lower values than these.

There are several ways to get around the possible disagreement between Sandage's and Weygandt's values of $\alpha$, from observations of the distant galaxies and Weygandt's value of $\alpha$, from measurements of the abundance of deuterium. Burton says, "The University of Texas has hypothesized that because galaxies evolve over a period of time, their $\alpha$, values depend on their mass. The essential point of the whole argument is that we look deeper into space we are also looking backward in time, and that the average brightness of the 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 Balmer lag.