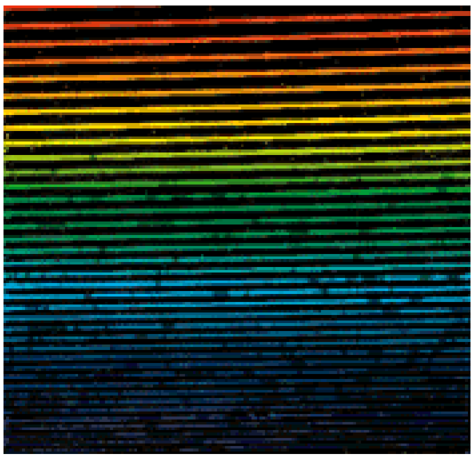

Image: Laurie Grace

Primordial Deuterium and the Big Bang

Nuclei of this hydrogen isotope formed in the first moments of the big bang. Their abundance offers clues to the early evolution of the universe and the nature of cosmic dark matter

by Craig J. Hogan

KECK TELESCOPE on Mauna Kea, Hawaii, gathered light from a distant quasar and concentrated it on the photodetector of a high-resolution spectroscope. The resulting bands of color (*above*) are marked by dark lines where intervening gases have absorbed light of specific wavelengths. Analysis of the characteristic line patterns for hydrogen gas can reveal the presence of the heavy isotope of the element deuterium.

SUBTOPICS:

The big bang model of the early universe is extraordinarily simple: it has no structure of any kind on scales larger than individual elementary particles. Even though the behavior it predicts is governed only by general relativity, the Standard Model of elementary particle physics and the energy distribution rules of basic thermodynamics, it appears to describe the primordial fireball almost perfectly.

Atomic nuclei that formed during the first seconds and minutes of the universe provide additional clues to events in the early universe and to its composition and structure today. The big bang produced a universe made almost entirely of hydrogen and helium. Deuterium, the heavy isotope of hydrogen, was made only at the beginning of the universe; thus, it serves as a particularly important marker. The atoms depends strongly on both the uniformity of

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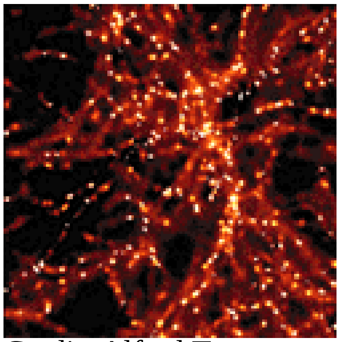
matter and the total amount of matter formed in the big bang. During the past few years, astronomers have for the first time begun to make reliable, direct measurements of deuterium in ancient gas clouds. Their results promise to provide a precise test of the big bang cosmogony.

The expansion of the universe appears to have started between 10 and 20 billion years ago. Everything was much closer together and much denser and hotter than it is now. When the universe was only one second old, its temperature was more than 10 billion degrees, 1,000 times hotter than the center of the sun. At that temperature, the distinctions between different kinds of matter and energy were not as definite as they are under current conditions: subatomic particles such as neutrons and protons constantly changed back and forth into one another, "cooked" by interactions with plentiful and energetic electrons, positrons and neutrinos. Neutrons are slightly heavier than protons, however; as things cooled, most of the matter settled into the more stable form of protons. As a result, when the temperature fell below 10 billion degrees and the intertransmutation stopped, there were about seven times as many protons as neutrons.

Out of the Primordial Furnace



Credit: Alfred T. Kamajian

MEASURING THE EARLY MAKEUP

When the universe was a few minutes old (at a temperature of about one billion degrees), the protons and neutrons cooled down enough to stick together into nuclei. Each neutron found a proton partner, creating a pair called a deuteron, and almost all the deuterons in turn stuck together into helium nuclei, which contain two protons and two neutrons. By the time primordial helium had formed, the density of the universe was too low to permit further fusion to form heavier elements in the time available; consequently, almost all the neutrons were incorporated into helium.

Without neutrons to hold them together, protons cannot bind into nuclei because of their electrical repulsion. Because of the limited neutron supply in the primordial fireball, six of every seven protons must therefore remain as isolated hydrogen nuclei. Consequently, the big bang model predicts that about one quarter of the mass of the normal matter of the universe is made of helium and the other three quarters of hydrogen. This simple prediction accords remarkably well with observations. Because hydrogen is the principal fuel of the stars of the universe, its predominance is the basic reason for starlight and sunlight.

During the formation of helium nuclei, perhaps only one in 10,000 deuterons remained unpaired. An even smaller fraction fused into nuclei heavier than helium, such as lithium. (All the other familiar elements, such as carbon and oxygen, were produced much later inside stars.) The exact percentages of helium, deuterium and lithium depend on only one parameter: the ratio of protons and neutrons--particles jointly categorized as baryons--to photons. The value of this ratio, known as *n* (the Greek letter eta), remains essentially constant as the universe expands; because we can measure the number of photons, knowing *n* tells us how much matter there is. This number is important for understanding the later evolution of the universe, because it can be compared with the actual amount of matter seen in stars and gas in galaxies, as well as the larger amount of unseen dark matter.

For the big bang to make the observed mix of light elements, *n* must be very small. The universe contains fewer than one baryon per billion photons. The temperature of the cosmic background radiation tells us directly the number of photons left over from the big bang; at present, there are about 411 photons per cubic centimeter of space. Hence, baryons should occur at a density of somewhat less than 0.4 per cubic meter. Although cosmologists know that *n* is small, estimates of its exact value currently vary by a factor of almost 10. The most precise and reliable indicators of *n* are the concentrations of primordial light elements, in particular deuterium. A fivefold increase in *n*, for example, would lead to a telltale 13-fold decrease in the amount of deuterium created.

The mere presence of deuterium sets an upper limit on *n* because the big bang is probably the primary source of deuterium in the universe, and later processing in stars gradually destroys it. One can think of deuterium as a kind of partially spent fuel like charcoal, left over because there was originally not time for all of it to burn completely to ash before the fire cooled. Nucleosynthesis in the big bang lasted only a few minutes, but the nuclear burning in stars lasts for millions or billions of years; as a result, any deuterium there is converted to helium or heavier elements. All the deuterium that we find must therefore be a remnant of the big bang--even the one molecule in 10,000 of seawater that contains a deuterium atom in place of a hydrogen atom.

Quasars and Gas Clouds

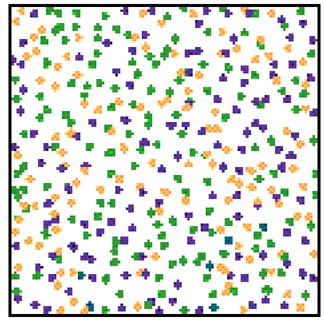


Image: Ian Warpole

NUCLEOSYNTHESIS

Determining the primordial ratio of deuterium to ordinary hydrogen should be highly informative, but it is not easy, because the universe is not as simple as it used to be. Astronomers can measure deuterium in clouds of atomic hydrogen gas between the stars of our galaxy, but the element's fragility renders the results suspect. We live in a polluted, dissipated, middle-aged galaxy whose gases have undergone a great deal of chemical processing over its 10-billion-year history. Deuterium is very readily destroyed in stars, even in their outer layers and their early prestellar evolution. Stars eject their envelopes when they die, and the gas in our galaxy has been in and out of stars many times. As a result, looking at nearby gas clouds can suggest only a lower limit to primordial deuterium abundance.

It would be much better if one could get hold of some truly pristine primordial material that had never undergone chemical evolution. Although we cannot bring such matter into the laboratory, we can look at its composition by its effect on the spectrum of light from distant sources. Bright quasars, the most luminous objects in the universe, are so far away that the light we see now left them when the universe was only one sixth to one quarter of its present size and perhaps only a tenth of its present age. On its way to us, the light from these quasars passes through clouds of gas that have not yet condensed into mature galaxies, and the light absorbed by these clouds gives clues to their composition. Some of the clouds that have been detected contain less than one thousandth the proportion of carbon and silicon (both stellar fusion products) seen in nearby space, a good sign that they retain very nearly the composition they had immediately after the big bang.

There is another advantage to looking so far away. The main component of these clouds, atomic hydrogen, absorbs light at a sharply defined set of ultraviolet wavelengths known as the Lyman series. Each of these absorption lines (so called because of the dark line it leaves in a spectrum) corresponds to the wavelength of a photon exactly energetic enough to excite the electron in a hydrogen atom to a particular energy level. These lines have colors that lie deep in the ultraviolet and cannot usually be seen from the ground because of atmospheric absorption; even the reddest (and most prominent) line, Lyman alpha, appears at a wavelength of 1,215 angstroms. Luckily, the expansion of the universe causes a "cosmological redshift" that lengthens the wavelengths of photons that reach the earth to the point where hydrogen absorption lines from sufficiently distant gas clouds reside comfortably within the visible range.

Lyman alpha appears in light from a typical quasar hundreds of times, each time from a different cloud along the line of sight at a different redshift and therefore at a different wavelength. The resulting spectrum is a slice of cosmic history, like a tree-ring sample or a Greenland ice core: these quasar absorption spectra record the history of the conversion of uniform gas from the early big bang into the discrete galaxies we see today over an enormous volume of space. This multiplicity of spectra offers another way to test the primordial character of the absorbing material: the big bang model predicts that all gas clouds from the early universe should have more or less the same composition. Measuring the abundances of different clouds at vast distances from us and from one another in both time and space will directly test cosmic uniformity.

In some of these clouds, we can determine from the quasar spectra both how much ordinary hydrogen there is and how much deuterium. We can separate the signal from deuterium because the added mass in the deuterium nucleus increases the energy required for atomic transitions by about one part in 4,000 (twice the ratio of a proton's mass to an electron's mass). As a result, the absorption spectrum of deuterium is similar to that of single-nucleon hydrogen, but all the lines show a shift toward the blue end of the spectrum equivalent to that arising from a motion of 82 kilometers per second toward the observer. In spectrographic measurements of a hydrogen cloud, deuterium registers as a faint blue-shifted "echo" of the hydrogen.

These spectra also record the velocity and temperature distribution of the atoms. Atoms traveling at different velocities absorb light at slightly different wavelengths because of the Doppler effect, which alters the apparent wavelength of light according to the relative motion of transmitter and receiver. Random thermal motions impel the hydrogen atoms at speeds of about 10 kilometers per second, causing a wavelength shift of one part in 30,000; because they are twice as heavy, deuterium atoms at the same temperature move at only about seven kilometers per second and therefore have a slightly different velocity distribution. A modern spectrograph can resolve these thermal velocity differences, as well as larger-scale collective flows.

Waiting for the Light

Although spectrographs can easily resolve the wavelength differences between ordinary hydrogen and deuterium, splitting the light of a distant quasar into 30,000 colors leaves very little intensity in each color. For more than 20 years, these observations proved too difficult. Many of us have spent long nights waiting for photons to drip one by one onto the detectors of the world's largest telescopes, only to find that the weather, instrument problems and, ultimately, just lack of time had prevented the accumulation of enough light for a convincing result. The technique is now practical only because of improved, more efficient detectors, the 10-meter Keck telescope in Hawaii and advanced high-resolution, high-throughput spectrographs such as the Keck HIRES.

After many unsuccessful attempts on smaller telescopes, my colleagues Antoinette Songaila and Lennox L. Cowie of the University of Hawaii were allocated their university's first science night on the Keck Telescope for this project in November 1993. They trained the telescope on a quasar known as 0014+813, famous among astronomers for its brightness--indeed, it was for some years the brightest single object known in the universe. From earlier studies by

Ray J. Weymann of the Observatories of the Carnegie Institution of Washington and Frederic Chaffee, Craig B. Foltz and Jill Bechtold of the University of Arizona and their collaborators, we knew that a fairly pristine gas cloud lay in front of this quasar.

The first Keck spectrum, obtained in only a few hours, was already of sufficiently high quality to show plausible signs of cosmic deuterium. That spectrum showed the absorption pattern for hydrogen gas moving at various velocities, and it showed an almost perfect echo of the Lyman alpha line with the characteristic blueshift of deuterium. The amount of absorption in this second signal would be caused by about two atoms of deuterium per 10,000 atoms of hydrogen. The result has since been independently confirmed by Robert F. Carswell of the University of Cambridge and his colleagues, using data from the four-meter Mayall Telescope at the Kitt Peak National Observatory in Arizona. Subsequent analysis has revealed that the deuterium absorption indeed displays an unusually narrow thermal spread of velocities, as expected.

It is possible that some of the absorption we saw was caused by a chance interposition of a small hydrogen cloud that just happens to be receding from us at 82 fewer kilometers per second than the main cloud we observed. In that case, the deuterium abundance would be less than we think. Although the a priori chance of such a coincidence on the first try is small, we ought to regard this estimate as only preliminary. Nevertheless, the effectiveness of the technique is clear. Absorbing clouds in front of many other quasars can be studied with the new technology; we will soon have a statistical sampling of deuterium in primordial material. In fact, our group and others have now published measurements and limits for eight different clouds.

One of the most intriguing results is a measurement by David Tytler and Scott Burles of the University of California at San Diego and Xiao-Ming Fan of Columbia University, who have found a ratio that is apparently almost a factor of 10 lower than our estimate. It remains to be seen whether their result represents the true primordial value. The lower abundance might be a result of deuterium burning in early stars or a sign that the production of deuterium was perhaps not as uniform as the big bang model predicts.

Clues to Dark Matter

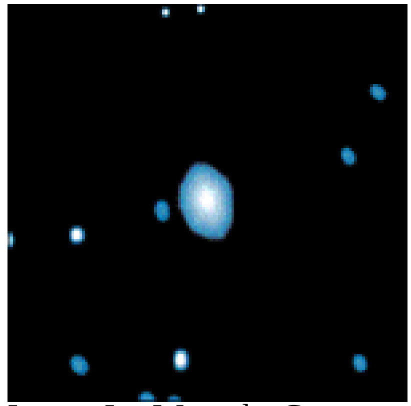


Image: Ian Worpole, Courtesy of the U.S. Naval Observatory

QUASAR, or quasistellar object, 0014+813 is one of the brightest objects known to exist in the cosmos. It appears here in a radiotelescope image. The light from this supermassive black hole at the center of a very young galaxy near the edge of the observable universe provided the first measurements of primordial deuterium.

If our higher value is correct, the amount of primordial deuterium would fit very well with the standard predictions of the big bang model for a value of *n* around two baryons per 10 billion photons. With this value of *n*, the big bang predictions are also consistent with the amounts of lithium in the oldest stars and estimates of primordial helium seen in nearby metal-poor galaxies. Confirmation of this result would be fabulous news. It would verify that cosmologists understand what happened only one second after the beginning of the expansion of the universe. In addition it would indicate that the history of matter at great distances is like that of nearby matter, as assumed in the simplest possible model of the universe.

This estimate of *n* fits reasonably well with the number of baryons we actually see in the universe today. The observed density of photons calls for about one atom for every 10 cubic meters of space. This is about the same as the number of atoms counted directly by adding up all the matter in the known gas, stars, planets and dust, including the quasar absorbers themselves; there is not a huge reservoir of unseen baryons. At the same time, observations suggest that an enormous quantity of dark matter is necessary to explain the gravitational behavior of galaxies and their halos--at least 10 times the mean density of the visible baryons. Thus, our high deuterium abundance indicates that this mass is not made of ordinary atomic matter.

Cosmologists have proposed many candidates for such nonbaryonic forms of dark matter. For example, the big bang predicts that the universe has almost as many neutrinos left over as photons. If each one had even a few billionths as much mass as a proton (equivalent to a few electron volts), neutrinos would contribute to the universe roughly as much mass as all the baryons put together. It is also possible that the early universe created some kind of leftover particle that we have not been able to produce in the laboratory. Either way, the big bang model, anchored by observation, provides a framework for predicting the astrophysical consequences of such new physical ideas.

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