PRIMORDIAL MATTER

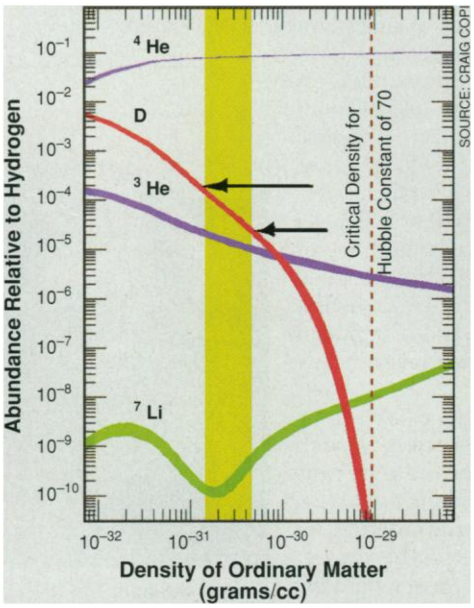
Astronomers Probe Creation By Measuring Isotopes

About a second after its creation in the big bang, the universe started to become a relatively familiar place. Until that point, if the big bang theory is right, swarms of energetic photons, neutrinos, and massive particles exchanged identities as easily as tap-dancing vaudevillians trade hats—a condition described by cosmologist Steven Weinberg as "unspeakably unfamiliar." After that first tick of the cosmic clock, as the universe cooled to less than 10 billion kelvin, neutrons and protons began chilling out, clinging together to form the hydrogen isotope called deuterium, most of which then fused to form helium and a trace of lithium. The remnants of that primordial puff of matter give astronomers their earliest probe of the big bang, the closest look they have at creation itself.

In the last 2 years, powerful new instruments such as the Keck 10-meter telescope in Hawaii have allowed astronomers to measure the amount of deuterium left in the early universe by that first burst of element creation. "This is the only way we have of seeing back to the first 3 minutes of the universe," says Joseph Silk, a cosmologist at the University of California, Berkeley. But unlike the triumphal confirmation of standard cosmology by the first detection of the cosmic background radiation—the microwave afterglow that last interacted with matter a few hundred thousand years after the big bang—the new observations carry both reassuring and disturbing implications for the canonical picture of creation.

On the one hand, says David Schramm, a cosmologist at the University of Chicago, the observations reassure astronomers that there is information to be gleaned from an analysis of the early universe's makeup. They show, he says, that deuterium existed "fresh out of the big bang" at higher levels than today, just as theory predicts. And because the amount of deuterium generated in the big bang drops steeply as the density of baryonic, or ordinary, matter increases (see graphic), deuterium's primordial abundance becomes a sensitive "baryometer." It can tell how much ordinary matter was forged in the big bang—and, when compared with other mass indicators, how much of the universe must take the form of exotic dark-matter particles. Says Schramm, "That's the headline."

The fine print is that the Keck observations, so far, have produced two very different values for the deuterium abundance. Worse, both of them conflict with measurements of helium isotopes in the nearby universe, which also provide clues—albeit far less direct ones—to the baryon density. The discrepancies between the primordial and nearby measurements could mean that astronomers have misunderstood how stars have created and consumed elements over the past 10 billion years—a major upheaval in its own right. Or, as a group of cosmologists at Ohio State University and the University of Pennsylvania



Recipes for a universe. As the density of ordinary matter goes up, the predicted abundance of particular isotopes shifts. Two deuterium measurements *(arrows)* differ by a factor of 10.

has argued, the disparities could mean that the theory of how the big bang created elements, known as big bang nucleosynthesis (BBNS), is "in crisis," requiring basic revisions in astronomers' picture of what went on during the cosmos's first moments.

Even more unsettling is the conflict between the two primordial measurements. If both are correct, and deuterium really does occur at different levels in the primordial universe depending on where you look, "that would require a very radical overhaul of what we think we understand about the early universe," says Silk. It even raises the awkward possibility of a "lumpy" big bang.

Primordial soup. The cosmos's first second is the domain of theory. As it cooled from unimaginably high temperatures, say theorists, nature's various forces split away from a primeval unity into their current asymmetries of strengths and ranges. Along the way, the basic constituents of matter took shape. One of these "phase transitions," for example, created a homogeneous fluid of quarks and gluons. As this featureless plasma cooled further, it coalesced into protons, neutrons, and other massive particles.

Flitting among them were the much lighter electrons and positrons, neutrinos, and massless photons. As they collided with the heavier particles, says Terry Walker of Ohio State University, they drove "a bunch of reactions that can interconvert neutrons and protons." As long as the temperature remained above 100 billion degrees, the reactions ran in both directions, keeping neutron and proton numbers about equal. At cooler temperatures, the slightly lighter protons began to win out at the expense of the neutrons, because the other particles were no longer energetic enough to supply the missing mass, through Einstein's mass-energy equivalence.

Finally, says Walker, the reactions stopped when they were effectively outrun by the cosmic expansion, and the neutron-proton ratio "froze out" at a fixed value. At this point, protons and neutrons still couldn't stick together to form more complex nuclei. But roughly a second to a few minutes into the big bang, background photons were no longer energetic enough to blast apart deuterium when it formed, removing a bottleneck in a series of fusion reactions. The reactions now surged ahead, funneling nearly all of the surviving neutrons into helium-4, the most tightly bound of all the light elements. "It's really just straightforward nuclear physics," says Craig Copi of the University of Chicago. "It's a lot like a hydrogen bomb."

At that point, the early universe is finally open to observation, because the products of that primordial burst of nuclear reactions were the raw materials for the universe we know. The bulk of the universe is hydrogen—protons that never combined into heavier nuclei, says Copi. In general accord with BBNS, most of the rest is helium.

Even more telling are the traces of deuterium that survived. If the reactions had been taking place in a star, where they run to completion, all the deuterium would have been turned into helium. But in the big bang expansion, nuclei eventually stopped encountering each other often enough to fuse, quenching the reactions before they were completely finished. The smaller the amount of baryonic matter packed into the nascent universe, the sooner the reactions would have stopped and the more deuterium would have survived. Less baryonic matter would also have favored the survival of helium-3, although the effect would not have been as dramatic as for deuterium. Helium-4 would show the opposite effect: Its abundance would decrease slightly as the baryon density decreased.

How to Duel With Deuterium

It's unnerving, to say the least, when two groups look at the same gauge and get completely different readings. But that's what has happened in the search for primordial deuterium, an isotope of hydrogen forged in the big bang that provides a direct indicator of the amount of ordinary matter in the universe (see main text).

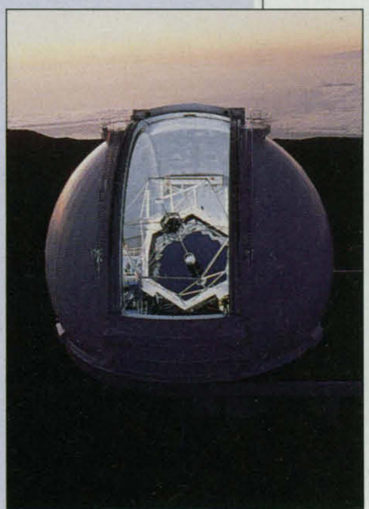
Last month, David Tytler, Xiao-Ming Fan, and Scott Burles of the University of California, San Diego, reported in *Nature* that they had measured the abundance of deuterium in gas clouds billions of light-years away in the early universe. They had followed the same procedure for measuring the isotope as had another group, led by Lennox Cowie of the University of Hawaii, that reported its results 2 years ago. But the Tytler group came up with a reading 10 times lower.

Measuring deuterium entails chasing shadows: looking for dark spectral lines in the light of bright, distant beacons called quasars. The lines indicate wavelengths at which far-off clouds of gas along the line of sight to a quasar are absorbing its light. And the wavelengths, in turn, reveal the composition of the clouds. Deuterium and neutral hydrogen absorb light at wavelengths that are only slightly offset from each other, but the lines from deuterium are often hundreds of times weaker. Distinguishing them requires the light-gathering power of the 10-meter Keck Telescope on Mauna Kea, the largest telescope in the world. With it, Tytler and company collected light from about 15 different quasars, looking for the coolest and most pristine possible distant clouds, in which the deuterium would be easiest to see.

Having homed in on a large cloud some 10 billion light-years away, they used the Keck's High Resolution Echelle Spectrograph to analyze its spectral lines. The relative strengths of the deuterium and hydrogen lines showed that the cloud contained about one deuterium atom for every 44,000 hydrogen atoms. Tytler says that yet-to-be-published data from a less distant cloud in front of a different quasar reveal nearly the same deuterium abundance.

The measurements were "certainly well done," says Craig Hogan of the University of Washington, Seattle, who with Cowie and their colleagues used the Keck and the same basic strategy to find 10 times as much deuterium along a sight line to a different cloud. "I consider the whole issue unsettled for the present." David Schramm, a cosmologist at the University of Chicago, says "either value is fine" for standard big bang theory, although the consequences for element-forming processes after the big bang diverge widely. But the story is different if both turn out to be right, he says: "No standard model gives variations on these [distance] scales." He adds, "Only time will tell if we eventually converge on a single value."

–J.G.



ROGER RESSMEYER/CORBIS

Eye on creation. The 10-meter Keck telescope.

For years, astronomers have had to infer primordial deuterium values from measurements of its levels nearby. Those measurements, made by directly sampling the thin interplanetary medium from spacecraft and by looking for deuterium "shadows" where starlight shines through interstellar clouds, suggested that relatively high levels of deuterium emerged from the primordial mix. This finding has constituted what Arnon Dar of the Space Research Institute of Technion in Haifa, Israel, calls "the strongest evidence that most of the matter in the universe is a mysterious nonbaryonic dark matter"—hypothetical particles that would not have affected element formation in the early universe. Astronomers already knew that the universe has to contain additional, unseen matter, to hold galaxies together against their own spin, for example. The deuterium measurements were high enough to suggest there is not enough ordinary matter to do the job.

These measurements, however, gave only an indirect look at the primordial deuterium abundance. The constituents of the solar system and the interstellar medium have already been processed in the bellies of generations of stars, which spewed out gases from which most of the original deuterium had been consumed. Astronomers had to infer a primordial value by figuring in billions of years of chemical evolution in the Milky Way.

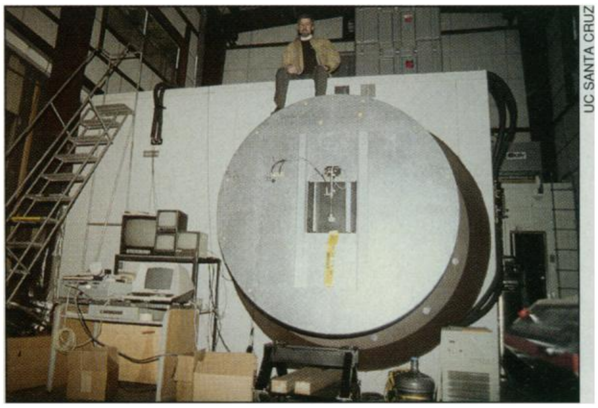
They finally got their first direct look at arguably primordial deuterium 2 years ago. Antoinette Songaila and Lennox Cowie of the University of Hawaii and Craig Hogan and Martin Rugers of the University of Washington, Seattle, used the Keck to measure the deuterium-to-hydrogen ratio in gas clouds some 10 billion light-years away (see box). The results were at the upper extreme of the inferred values or even beyond them, said some theorists—high enough that they surprised even some advocates of exotic forms of dark matter.

Primordial deuterium abundances of that magnitude were potentially worrisome, says Hogan, because "when stars destroy deuterium, the first thing they do is turn it into helium-3." And in the Milky Way, he says, the high abundance of helium-3 expected to result from the destruction of so much deuterium "is just not there." Hogan and others including Schramm and Michael Turner at Chicago believe that if the primordial abundance is indeed that high, the problem may lie in the traditional view of helium-3 evolution in the galaxy, which holds that low-mass stars—the commonest kind of stars—are net producers of it when they burn hydrogen and deuterium.

Instead, Hogan proposes, a weak mixing action in the outer envelopes of these stars could stir the helium-3 deeply enough to slowly "cook" it into heavier nuclei before the stars blow them off in their stellar winds. If this is happening, says Hogan, "the constraint disappears." High deuterium in the primordial universe wouldn't necessarily show up as helium-3 today.

There may be other signs of this stellar cooking: A group led by geophysicist G. J. Wasserburg at the California Institute of Technology recently proposed this mechanism to explain what he calls "crazy" isotopic ratios of oxygen in meteorites and carbon in stars. And Schramm points out that recent measurements of interstellar helium-3 by the Ulysses spacecraft as it passed over the sun's north pole, where ions from interstellar space leak into the solar system, yielded figures in the same ballpark as those from within the solar system. The comparison implied that the isotope's abundance hasn't changed dramatically over the age of the solar system, suggesting that stars don't act as helium-3 factories, contrary to expectations. "The observations are saying, 'Hold it—chemical evolution theory is off,' " says Schramm.

Deuterium double take. Those observations could help theorists out of their bind if the primordial deuterium abundance is high. The new measurements, however, made with the Keck by David Tytler, Xiao-Ming Fan, and Scott Burles at the University of California, San Diego (UCSD), yield



UC SANTA CRUZ

Getting a line on deuterium. The high-resolution spectrograph at the Keck telescope and its builder, Steven Vogt.

a deuterium abundance in an even more distant cloud almost 10 times lower than the earlier Keck measurement. If this value represents the true primordial abundance, then the scarcity of helium-3 in the present universe is no longer a puzzle. But the baryon-rich primordial universe it implies would have produced a higher ratio of primordial helium-4 to hydrogen than observers seem to find when they look at clouds in the nearby intergalactic medium.

There's no way to measure primordial helium-4 directly, for this isotope is continuously produced by stars. But astronomers can estimate how much of the helium in any given cloud is primordial and how much was generated in the stellar furnaces by taking into account the cloud's complement of heavier elements, which are only produced in stars. It's an uncertain process, but the results don't mesh comfortably with the Tytler group's measurements, says Bernard Pagel, a noted helium observer at NORDITA in Copenhagen, Denmark. "The Tytler result," he says, "stretches existing uncertainties in helium to their limits."

Such conflicts have led some researchers to question the standard theory of BBNS. When Walker, Naoya Hata, Robert Scherrer, Gary Steigman, and David Thomas at Ohio State, and Sidney Bludman and Paul Langacker at the University of Pennsylvania combined abundance measurements for all the light elements into a rigorous statistical analysis, they found the fewest discrepancies when they took numbers closer to the lower deuterium value as the correct ones. But even then, as implied by the title of the paper they published last November in *Physical Review Letters*—"Big Bang Nucleosynthesis in Crisis?"—they could see no easy way out of the contradictions without changing the standard picture of nucleosynthesis.

The team proposes that something might have slowed down the big bang during nucleosynthesis, allowing time for more neutrons to transmute into protons before the "freeze-out," thereby depleting the universe of neutrons and slightly reducing the amount of helium-4 that should emerge. If one of the three types of neutrinos, a particle commonly thought to be massless, actually does have substantial mass, it would have been moving more slowly in the early universe, taking just the right amount of oomph out of the expansion. The team chose the tau neutrino because it is the only kind whose properties remain uncertain enough to allow for such a large mass.

Unfortunately, most physicists believe that option strains credulity. "There is no experimental proof against a [very] massive tau," says David Caldwell of the University of California, Santa Barbara. "But I would bet a lot of money against it." There's only one thing for sure, says Karsten Jedamzik of Lawrence Livermore National Laboratory: "Whether the deuterium is high or low, you have problems."

Theorists also have to contend with the even more dizzying possibility that both measurements will turn out to be correct. If that's the case, says UCSD's George Fuller, "the first thing I would look at is whether [distant stars] could do it"—produce an uneven deuterium abundance by chewing up unexpectedly large amounts of deuterium in some places but not others in the early universe. If that didn't work, says Fuller, then "way down on the list," theorists would have to consider an inhomogeneous big bang, even though most calculations have shown that "nature seems to abhor an inhomogeneity."

Astronomers will have to take more readings from the deuterium baryometer before theorists will know which way to turn, says Tytler: "In order to show, for example, that there's a real variation, we would need some more high-precision measurements." The worst of cosmologists' problems will go away, says Tytler, "if we find the same [deuterium abundance] in different places," showing that one or the other of the present measurements is spurious. But even then, theorists don't expect to emerge unscathed from their closest brush with the big bang.

–James Glanz

SEEDS OF STRUCTURE

Microwave Wrinkles Promise Vital Statistics of the Cosmos

As a location to measure the background noise of the universe, Saskatoon, Canada, has been called the poor man's South Pole. Located in the midst of the Great Plains, 320 kilometers north of the Montana border, it is cold, dry, and flat. The result is a stable, uniformly cold air mass through which to view the cosmos, which happens to be a critical advantage for astrophysicists trying to measure variations of just one part in 100,000 in the temperature of a cold bath of microwaves known as the cosmic microwave background (CMB). Saskatoon's other advantage is simple, says Princeton University astrophysicist Lyman Page: It is the only place for hundreds of miles around that has "multiple hardware stores, a university, and an airport."

The right hardware and vantage point are what it takes these days to pursue questions that once belonged to priests and philosophers—questions about the origin, history, and future of the universe. Computer simulations of the CMB's formation in the early universe, together with experimental observations like those that Page and his colleagues are making in their Saskatoon experiment, called Bigplate, have persuaded astrophysicists and cosmologists that the CMB is about to yield some definitive answers. The CMB provides "a snapshot of the universe in its infancy," says University of Pennsylvania astrophysicist Paul Steinhardt. And the cosmic infancy, like human childhood, holds clues to much of what followed.

Since NASA's COBE satellite first revealed the fluctuations in the CMB in 1992, that promise has sparked what Steinhardt calls a "theoretical industry" dedicated to showing what could be teased out of better observations. Among the prizes are values of the Hubble constant, which is the rate at which the universe is expanding; of omega, the density of the universe, which determines whether or not the universe will expand forever; of omega baryon, the density of ordinary matter in the universe; and even of the cosmological constant, which is the energy density of the universe. "It is truly extraordinary," says Steinhardt, "the first time we have this window on the universe, a singular event in human history."

Getting a clear view through this window, however, will require observations more extensive than any of the dozen or so Earth-bound experiments now under way can deliver. But with the April announcement by NASA and the European Space Agency that, early in the next century, they will launch spacecraft to measure variations in the CMB with unprecedented accuracy, astrophysicists