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TIME

HOW THE STARS WERE BORN

FOR THE FIRST TIME EVER, SCIENTISTS TAKE AN INCREDIBLE JOURNEY TO THE DAWN OF THE UNIVERSE

BY MICHAEL D. LEMONICK

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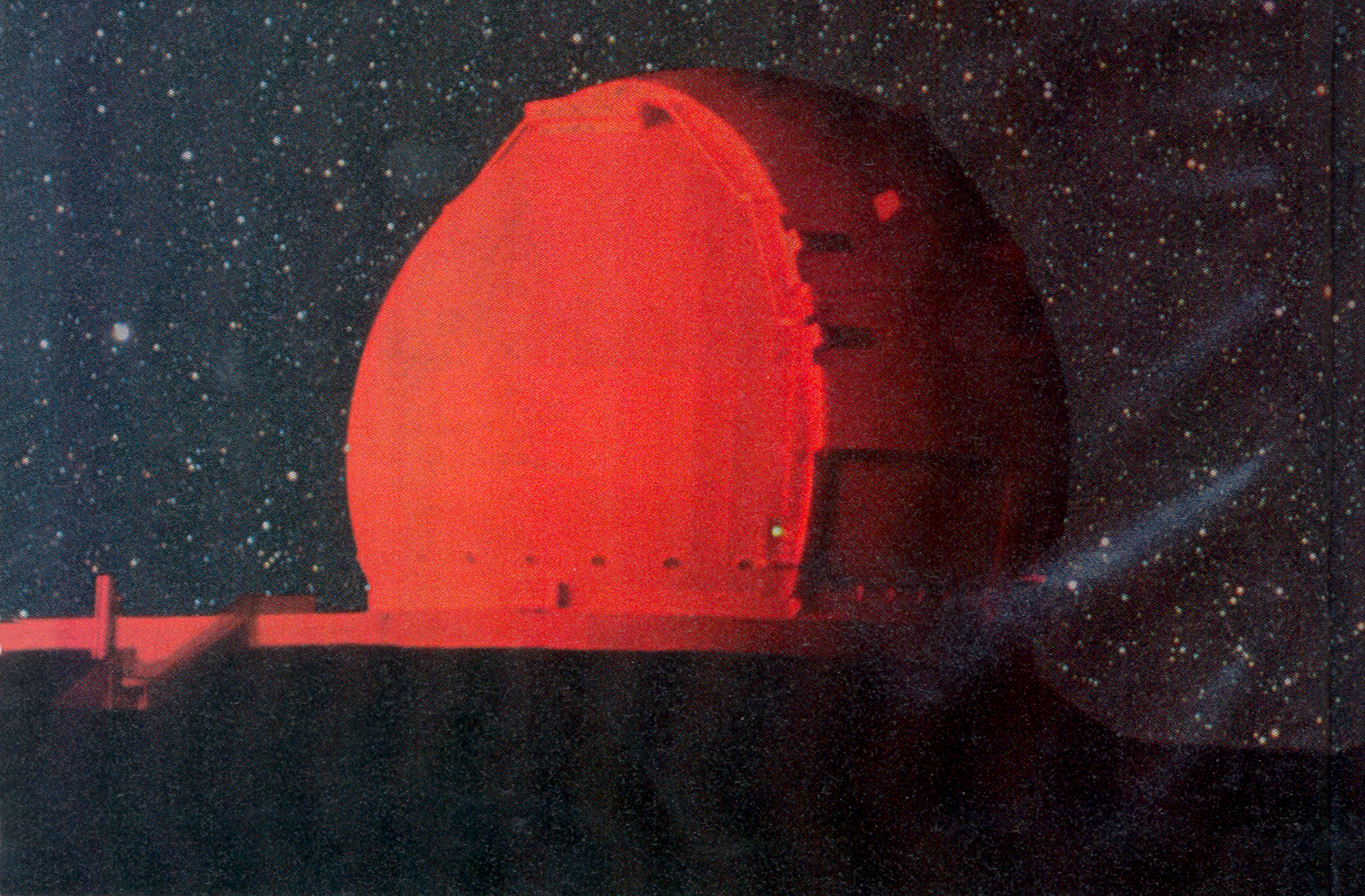
Let There Be Light

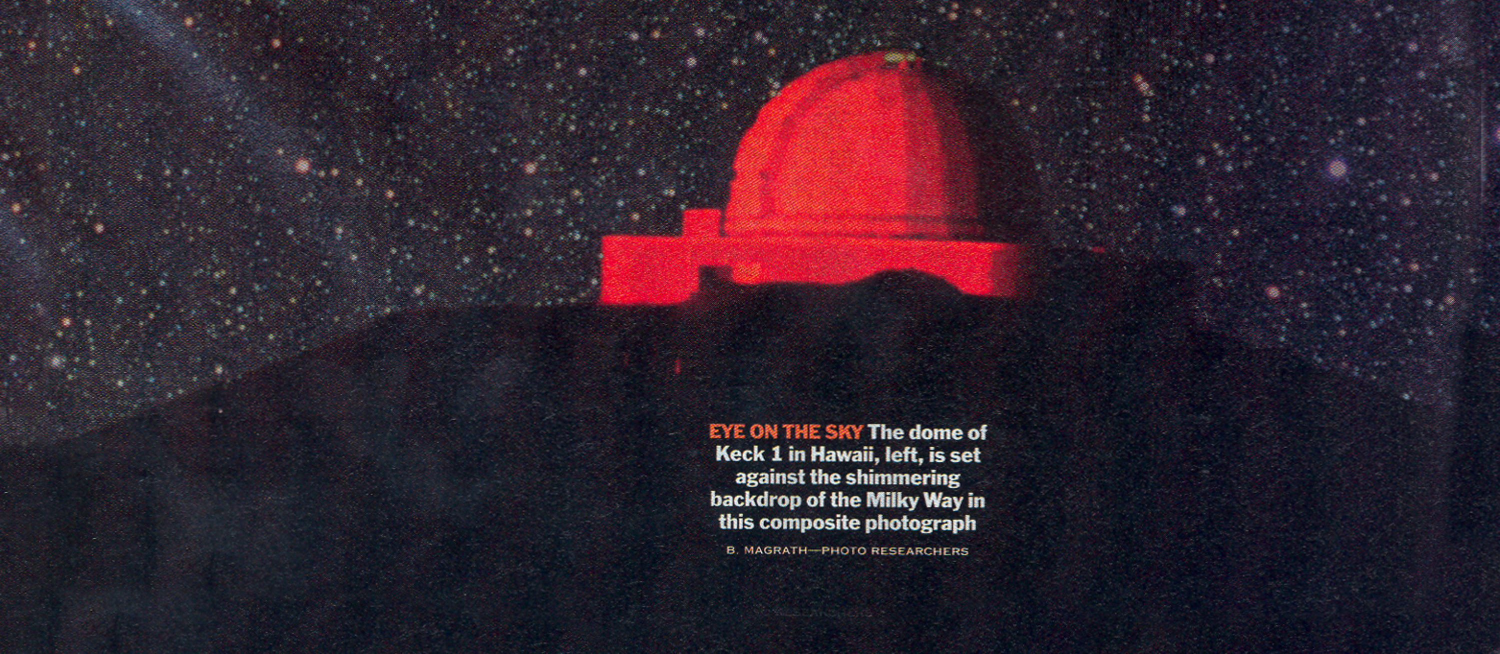
400,000 YEARS AFTER THE BIG BANG, THE COSMOS WENT



BLACK. HERE'S WHAT HAPPENED NEXT BY MICHAEL D. LEMONICK

RICHARD ELLIS PACES IMPATIENTLY BACK and forth across a small room lined with computer terminals, trying to contain his mounting frustration. The British-born astronomer, now at Caltech, has been granted a single precious night to use one of the twin Keck telescopes, among the most powerful in the world. Last night he and his observing partner, a graduate student named Dan Stark, flew 3,000 miles, from Southern California to Hawaii, where the Kecks are located. And during most of the afternoon and early evening today, they've made their final plans for the "run," as astronomers call a night of peering into the heavens.

But things are not going right. It isn't the weather, which is what usually trips up stargazers. Here at Keck headquarters in the sleepy town of Waimea, nestled in the midst of cattle-ranching country on Hawaii's Big Island, thick clouds are scudding past, occasionally dipping low enough to send a driving mist across the grassy hills. But the telescopes are some 25 miles away and more than two miles up, in the thin, frigid air at the summit of the extinct volcano Mauna Kea. At an altitude of nearly 14,000 ft., the observatory sits well above the cloud deck. Live video-camera images piped down to the Waimea control room show white domes silhouetted against a fading but crystal-clear sky.



EYE ON THE SKY The dome of Keck 1 in Hawaii, left, is set against the shimmering backdrop of the Milky Way in this composite photograph

B. MAGRATH—PHOTO RESEARCHERS

The problem is that Keck 2, the scope Ellis and Stark have been assigned for the night, stubbornly refuses to focus. Time and again, the professional telescope operator who sits in a control room up on the summit and actually runs the mammoth instrument has issued the command that tells it to focus. Time and again, the focusing routine has responded to his commands by crashing. For half an hour, engineers have been trying to figure out what is going on—while the first of the precious celestial objects on Ellis and Stark's observing schedule sinks inexorably toward the horizon. "This is pretty profound," says Ellis, bitterly. "If you can't focus the telescope, you're stuffed."

No astronomer likes to be cheated out of an observing night, whether the quarry is a mundane moon of Jupiter or an exotic quasar halfway across the cosmos. But Ellis has special cause for frustration: he's looking for something far more elusive than any quasar. Tonight he intended to bag something most astronomers consider next to impossible: the most distant galaxy ever seen—and not the farthest by just a little bit. The current record for distance, held by another giant Mauna Kea observatory, Japan's Subaru telescope, is for a galaxy whose light started its journey to Earth a billion years or so after the Big Bang. But Ellis and Stark suspect they have found not one but six galaxies from an astonishing half a billion years earlier still. Tonight's run could confirm it.

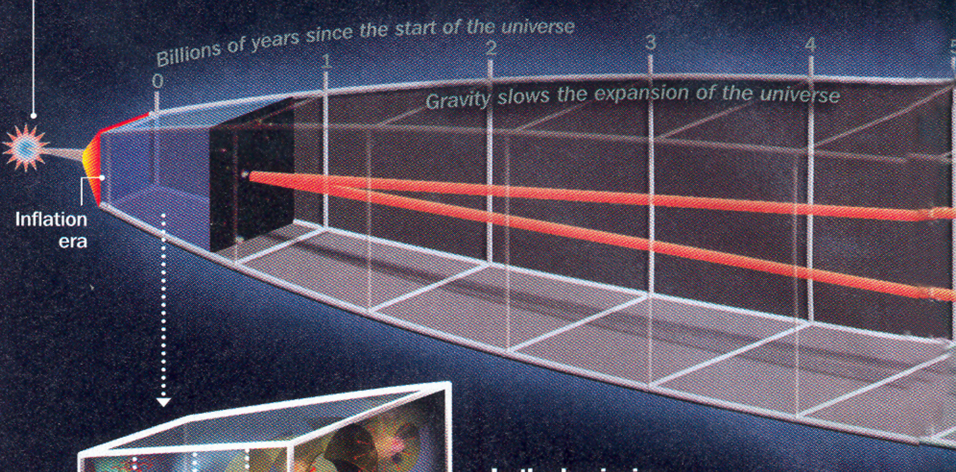
A discovery like that would give Ellis bragging rights at astronomy conferences for years to come, and it would let Stark finish his dissertation with a dramatic flourish. But far more important, it would give astrophysicists their first real glimpse into a crucial and mysterious era in the evolution of the cosmos. Known as the Dark Ages of the universe, it's the 200 million-year period (more or less) after the last flash of light from the Big Bang faded and the first blush of sun-like stars began to appear. What happened during the Dark Ages set the stage for the cosmos we see today, with its billions of magnificent galaxies and everything that they contain—the shimmering gas clouds, the fiery stars, the tiny planets, the mammoth black holes.

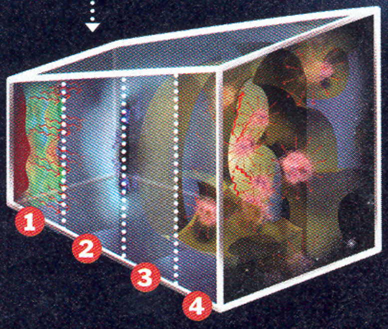
When the Dark Ages began, the cosmos was a formless sea of particles; by the time it ended, just a couple hundred million years later, the universe was alight with young stars gathered into nascent galaxies. It was during the Dark Ages that the chemical elements we know so well—carbon, oxygen, nitrogen and most of the rest—were first forged out of primordial hydrogen and helium. And it was during this time that the

Illuminating a Dark Age

Looking for the beginning of time ...

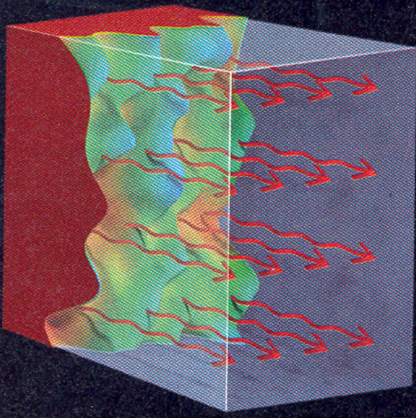
Big Bang About 13.7 billion years ago, the universe burst into existence, creating everything it is now

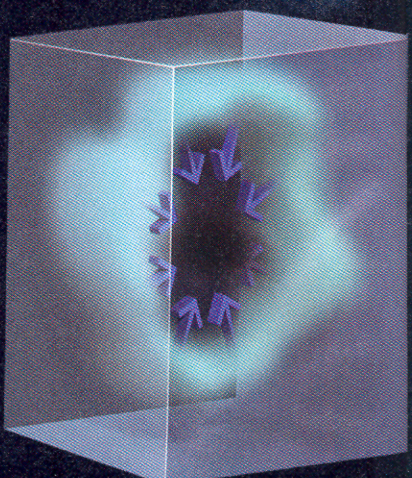




In the beginning ...
Half a million years after the Big Bang, the cosmos went **dark.** Two hundred million years later, **baby galaxies** began to shine. What happened in between laid the foundations for the modern universe

Inside the Dark Era





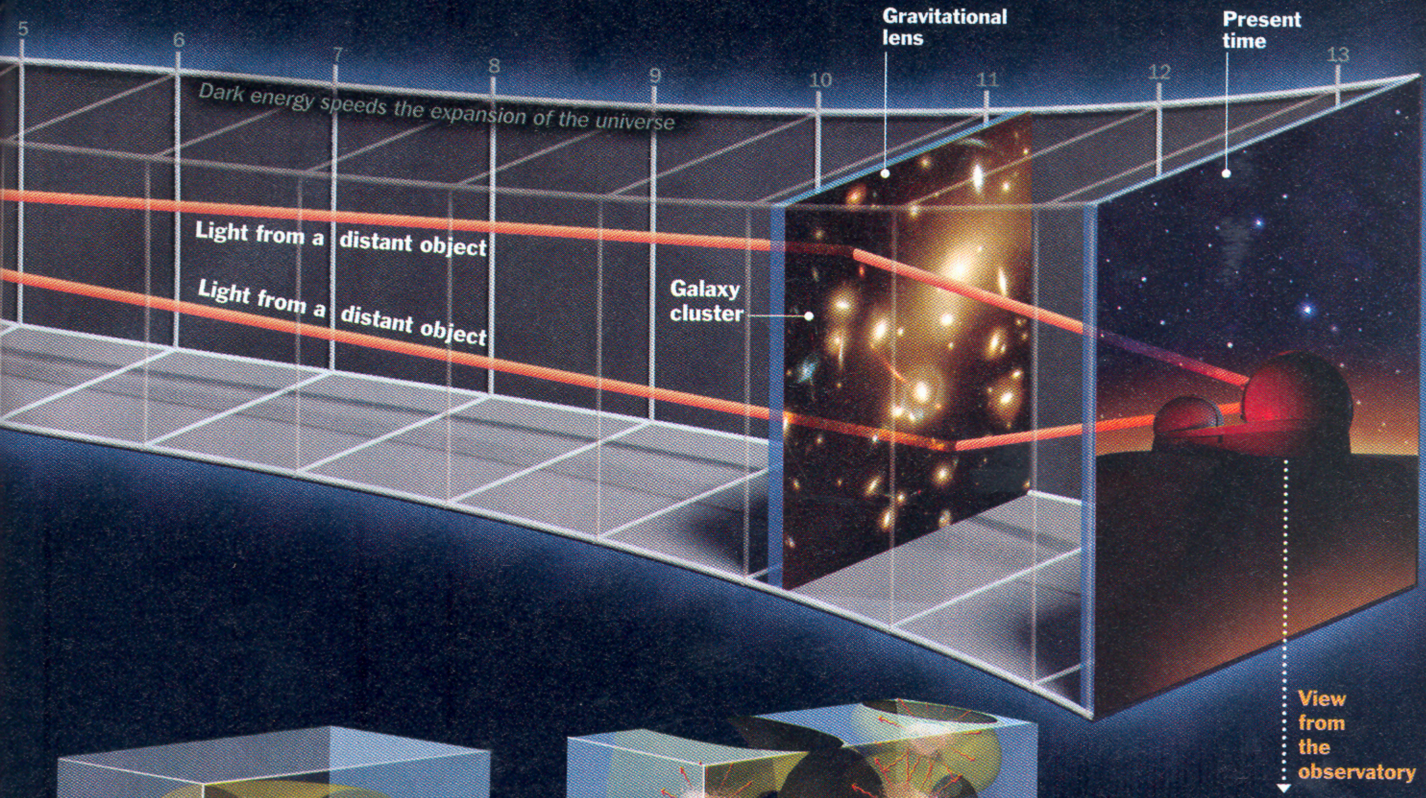
1 THE DARK AGES BEGIN
When the cosmos was about **400,000 years** old, it had cooled to about the temperature of the surface of the sun, allowing subatomic particles to combine for the first time into **atoms.** The last burst of light from the Big Bang shone forth at that time; it is still detectable today in the form of a faint whisper of **microwaves** streaming from all directions in space. The discovery of those microwaves in 1964 confirmed the existence of the Big Bang

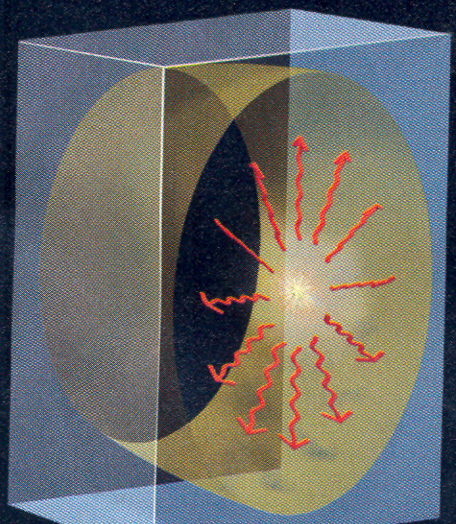
2 DARK MATTER
Accounting for a bigger portion of matter than ordinary atoms, **dark-matter particles** were spread unevenly through the cosmos; areas of higher concentration drew in **hydrogen** and **helium gas,** gradually forming the **first stars** dense enough to burst into thermonuclear flame

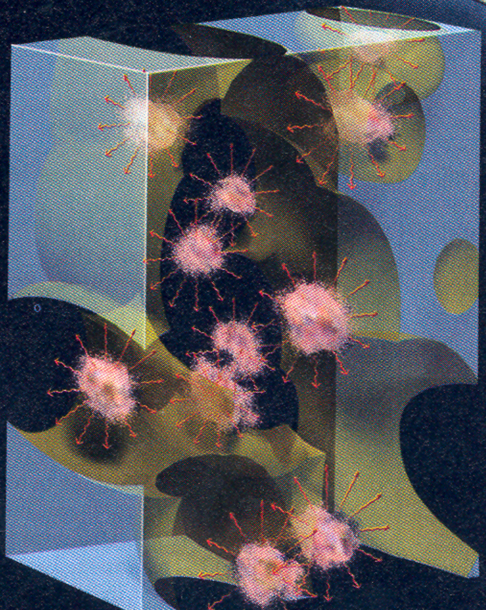
How the universe grew from a murky soup to twinkling galaxies

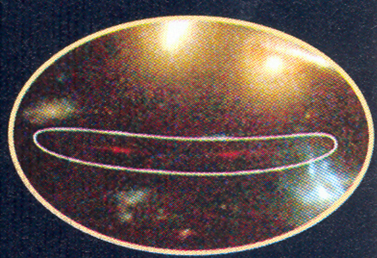
... 13.7 billion years later

Albert Einstein suggested that **gravity** from a massive foreground object could distort and magnify background objects. By looking through a **cluster of galaxies,** astronomers have now found the magnified images of much more distant galaxies









3 FIRST STARS

The earliest stars were massive, weighing in at 20 to more than 100 times the mass of the sun. The crushing pressures at their cores made them burn through their nuclear fuel in only a million years or so and caused them to spew radiation so intense that it kept other stars from forming. The first **"galaxies"** might have consisted of clouds of hydrogen and helium surrounding just one **mega-star**

4 END OF THE DARK AGES

The death of the mega-stars triggered the formation of normal stars, creating the first recognizable **dwarf galaxies.** Their radiation in turn burned through the remaining shrouds of hydrogen, bringing the dark ages to a close

What they're really seeing

A team of astrophysicists using the Keck and Hubble telescopes has found distant galaxies warped into odd, elongated shapes, as though they were being glimpsed through a cosmic fun-house mirror. The light from those galaxies ordinarily could never be detected through existing telescopes

TIME Graphic by Joe Lertola

Sources: Professor Avi Loeb, Harvard University; Professor Richard Ellis, Caltech

GALAXY IMAGE: JEAN-PAUL KNEIB, RICHARD ELLIS AND NASA/ESA great structures of the modern universe—superclusters of thousands of galaxies stretching across millions of light-years—began to assemble.

UNRAVELING A MYSTERY

SO FAR, HOWEVER, EVEN THE MIGHTIEST TELescopes haven't been able to penetrate into that murky era. "We have a photo album of the universe," says Avi Loeb, a theoretical astrophysicist at Harvard University, "but it's missing pages—as though you had pictures of a child as an infant and then as a teenager, with nothing in between."

The full answer may have to wait for a new generation of telescopes expected to come on line within the next decade. In astronomy, size matters, especially for faraway objects. The bigger a telescope, the more of a distant galaxy's meager light it can gather—just as a swimming pool catches more rain than a bucket. So astronomers are looking forward to a ground-based monster with nearly 10 times the light-gathering area of the Keck, a space telescope more than 10 times as big as the Hubble and several radio telescopes with unprecedented sensitivity. Meanwhile, using the basic laws of physics, sophisticated computer simulations and tantalizing hints from existing telescopes, astronomers have put together a plausible scenario of what must have happened during the Dark Ages.

The first of those hints comes from the universe-wide flash of light that followed nearly half a million years after the Big Bang. Before that flash occurred, according to the widely accepted "standard model" of cosmology, our entire cosmos had swelled from a space smaller than an atom to something 100 billion miles across. It was then a seething maelstrom of matter so hot that subatomic particles trying to form into atoms would have been blasted apart instantly and so dense that light couldn't have traveled more than a short distance before being absorbed. If you could somehow live long enough to look around in such conditions, you would see nothing but brilliant light in all directions.

But as the universe expanded, it finally cooled down enough to allow atoms to form and light to shine out across open space. The accidental discovery of that light back in the 1960s convinced astronomers that the Big Bang was a real event, not just a theoretical construct.

For regular coverage of space and science, check out Michael Lemonick's Eye on Science blog at **time.com**

THOMAS MICHAEL ALLEMAN FOR TIME

THE GALAXY HUNTER RICHARD ELLIS
With skill and patience he has amassed an extraordinary record of discoveries. His newest takes him within 500 million years of the Big Bang—right to the edge of the Dark Ages

That first detection of the remnants of the Big Bang was crude, but a series of increasingly sophisticated instruments, culminating in the Wilkinson Microwave Anisotropy Probe (WMAP) satellite in 2003, have laid bare the structure of the 400,000-year-old cosmos—only a few hundred-thousandths of its present age—in surprising detail. This was the baby picture Loeb referred to. At that point, the universe was still a very simple place. "You can summarize the initial conditions," says Loeb, "on a single sheet of paper." Some regions were a tiny bit denser than average and some a little more sparse. Most of the stuff in it—then and still today—was the mysterious dark matter that nobody has yet identified, largely because it doesn't produce light of any sort. The rest was mostly hydrogen, with a bit of helium mixed in. So far, the universe hadn't done much of anything.

THE FIRST STARS

AT THE START OF THE DARK AGES, THERE WERE no galaxies, no stars, no planets. Even if there had been, we wouldn't be able to spot them. That's because hydrogen-gas clouds are nearly opaque to visible light; no ordinary telescope will ever be able to see what happened afterward. Yet somehow the matter that started as a sea of individual atoms managed to transform itself into something

MAX AGUILERA-HELLWEG FOR TIME

THE RADIO ASTRONOMER
JACQUELINE HEWITT
She's building an array of antennas sensitive enough to hear the whisper of hydrogen at the edge of the cosmos

AGUILERA-HELLWEG FOR TIME

THE THEORIST
AVI LOEB
In the early '90s he spearheaded a study of the Dark Ages with the only tools on hand at the time: powerful computers

more. So back in the early 1990s, Loeb began lobbying theorists to make a major push to deduce through computer simulations how the first stars formed. The plan was to re-create the young universe digitally, plug in equations for the relevant physics and see what must have happened.

At first, the simulations agree, gravity was the only force at work. Regions of higher density drew matter to them, becoming denser still—a pattern preserved to this day in the distribution of galaxies, with huge clusters where there were high-density regions back then and great voids in between. Eventually, clouds of hydrogen became so dense that their cores ignited with the fires of thermonuclear reactions—the sustained hydrogen-bomb explosions, in essence, that we know as stars. But whereas the familiar stars of the Milky Way are mostly similar in mass to the sun, these first stars were, on average, gigantic—at least 25 times as massive as the sun and ranging as much as 100 times as massive, if not more. A star that big burns very hot, shining perhaps a million times brighter than the sun and generating a wind of particles that pushes the surrounding gases outward, keeping them from collapsing on their own to form new stars. The very first galaxies in the young universe may well have been microgalaxies, as theorist Mike Norman of the University of California at San Diego calls them: each one a single, huge, superhot star, surrounded by a halo of hydrogen.

Because they were so hot, the first stars would have poured out not just visible light, but also copious amounts of high-energy ultraviolet radiation. One effect of that radiation would have been to knock apart hydrogen atoms, thus destroying their ability to block light. That process is known as reionization, and those stars, forming perhaps 100 million years into the Dark Ages, or roughly at the era's midpoint, might have rendered the universe transparent on their own if they had lived long enough. But unlike the sun, which has survived 5 billion years so far and should live another 5 billion, those stars lasted only a paltry million years. If the first stars formed 100 million years after the Dark Ages began, they were gone by 101 million years. As they died, the smaller of the stars exploded and spewed their contents back into space, while the bigger ones formed black holes.

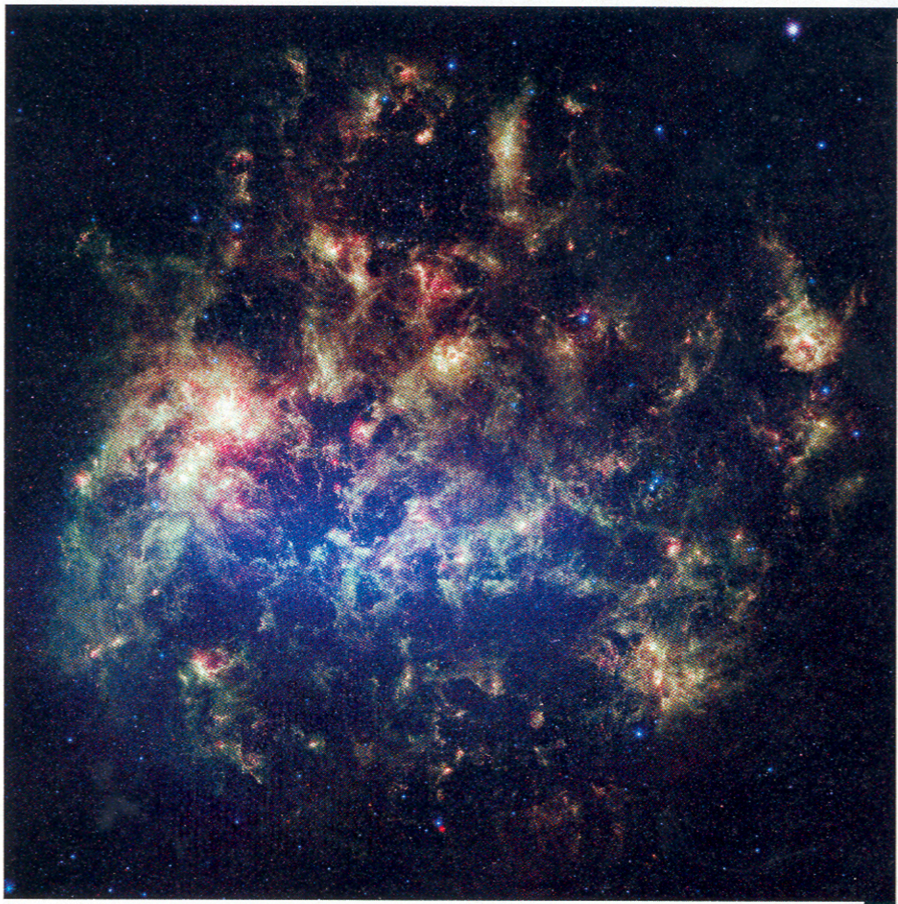
BURNING AWAY THE COSMIC FOG

AS IN ANY OTHER FUSION REACTION, THE fires that powered these short-lived stars worked by forcing simple hydrogen and helium atoms to meld into heavier, more complex elements. The stars that died explosively spiked the surrounding gas clouds with elements like oxygen and carbon, which had never existed before. Billions of years later, the elements forged in stars like these would be assembled into planets, organic molecules and, ultimately, human beings. At the time, though, they served simply to change the chemistry of the clouds, allowing them to collapse into far smaller objects than they could before. The second generation of stars, incorporating the ashes of the first, arose almost immediately. They were much more like the sun, in both composition and size. And like the sun, they would have started out generating lots of ultraviolet light before settling down to a more sedate existence.

It's this radiation—the ultraviolet light from hot, newly formed stars—that many theorists suspect finally reionized the remaining hydrogen, making it transparent again and bringing the Dark Ages to a close. Others suggest that the process may have been powered instead by black holes spewing out X-rays and ultraviolet light. Or it may have been a combination of hot stars and black holes that cleared the hydrogen and put an end to the Dark Ages.

In any event, the accepted scenario is that this new generation of small galaxies, containing no more than a million second-generation stars, gradually collided, merging to form ever bigger objects that eventually reached the size of the Milky Way. One piece of evidence: the faintest and oldest galaxies found in any great number by the Hubble telescope tend to be small and irregular in shape, not the majestic spirals and huge elliptical galaxies that formed later. Another hint that the merger theory is correct is that the collisions are still going on today. Astronomers can see hundreds of colliding galaxies in their telescopes, and our own Milky Way is still slowly gobbling up the half a dozen or so dwarf galaxies that surround it.

Guessing how the very first stars formed is relatively easy, since the universe was so simple at the start of the Dark Ages.



MARGARET MEIXNER—STSCI/JPL/CALTECH/NASA

RELIC OF THE PAST
Astronomers believe the first galaxies may have looked like this one, which is called the Large Magellanic Cloud

By the end, however, things were starting to get complicated. The stars had begun to affect their environment, and the environment in turn affected the stars in feedback loops that nobody has completely figured out. That's why astronomers want to test their theories with observation, and they will need a new generation of telescopes to do so.

SEEING THE UNSEEABLE

TO SPOT THE EARLIEST OBJECTS, HOWEVER, astronomers will have to stop looking for ordinary light. The universe has expanded vastly since its earliest days—but it isn't that galaxies and other objects are flying apart. Rather, it's that space itself has been stretching—a difficult concept even for a physicist to grasp, but which must be true according to the equations of relativity. Cosmologists say you should imagine the universe as a balloon with dots painted on its surface. As the balloon inflates, the dots will get farther apart—not because they're sliding around but because the balloon is stretching.

That being the case, a light beam traveling through expanding space is stretched as well, its wavelength getting longer as it goes. Long-wavelength light is red; stretch it out longer and it becomes infrared light and then microwaves and, finally, long-wavelength radio waves. The flash that came from the Big Bang started out as visible light; by now, 13.7 billion years later, it's still streaming through space, but it has been stretched so much that astronomers have to use microwave antennas to detect it. The earliest galaxies came after the Big Bang, so their light isn't quite as old, hasn't been traveling as long and thus isn't stretched as much. That light should be detectable not as microwaves but as infrared—which is why the new telescopes will be fitted with infrared sensors. It's also why the James Webb telescope, NASA's planned successor to the Hubble, will be optimized to see infrared, not visible light.

Still other telescopes will be trying to take pictures not of the first stars and galaxies, but of the clouds of hydrogen atoms they formed from and that they eventually destroyed. The hydrogen atoms emitted radiation too, in the form of radio waves, and several competing projects in various stages of completion in India, China, the Netherlands and Australia are being designed to see them. The last, known as the Mileura Widefield Array, is considered the most promising because its 500 separate antennas will be located on a remote cattle station in western Australia, far from any interference from earthly radio broadcasts. "The South Pole would be good too," says Jacqueline Hewitt, director of the Institute for Astrophysics and Space Research at M.I.T., which is a partner in the project, "but this is a bit more accessible. We'll need to cut some roads, though."

What makes Mileura and the other projects so powerful is that by tuning the receivers to different radio frequencies, they will be able to pick up signals broadcast by hydrogen atoms at different periods in the Dark Ages. When you map cosmic hydrogen at, say, 50 million years after the Big Bang—before the first stars had a chance to form—then at 100 million, 200 million or half a billion years later, you get a series of snapshots. Combine them, says Loeb, and "you'll be able to make a 3-D picture of hydrogen gas as the universe evolves. At some point, you'll start to see holes, like Swiss cheese," as the gas clouds become ionized and transparent. Precisely how the holes grow and merge over time will help determine whether the clearing out is being done by small galaxies, big black holes or something entirely different—and depending on which it is, some theorists could be vindicated and others refuted. But astronomers will at last have an answer to the mystery they have puzzled over for a decade and a half.

TANTALIZING CLUES

IN THE MEANTIME, OBSERVERS HAVE BEEN chipping away at this mystery as best they can with the tools they have. One important clue comes from the observation of the

> “We have a photo album of the universe including baby pictures, but we're missing some pages.”
> —AVI LOEB, Harvard

most distant quasars—objects believed to be giant black holes swallowing huge volumes of gas at the cores of young galaxies. The Sloan Digital Sky Survey, a comprehensive scan of the heavens, has turned up several of these from about a billion years after the Big Bang. By watching how the light of quasars is altered by surrounding gas, astronomers have concluded that there was still some atomic hydrogen around then, although not much.

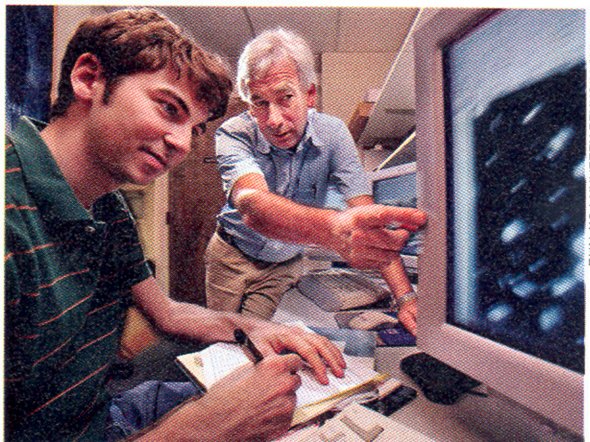
But the WMAP satellite, launched to look for light left from the Big Bang using a broadly analogous technique, determined the clearing out of hydrogen between the stars was well under way much earlier, just half a billion years post–Big Bang. "Theorists have been telling us that it should have happened fairly quickly once it began," says Michael Strauss, a Princeton University astronomer and deputy project scientist for the Sloan survey. "But the observations may be telling us otherwise."

Indeed, observations often take theorists by surprise. Last fall a focus on one tiny region of the universe by the Hubble, the Spitzer space telescope (which operates in infrared wavelengths) and the European Space Organization's ground-based Very Large Telescope in Chile revealed the existence of a galaxy dating to about 1 billion years after the Big Bang that was far larger and more mature looking than the primordial dwarf galaxies everyone assumed they would see. "It was unexpected," admits Mark Dickinson of the National Optical Astronomy Observatory, in Tucson, Ariz., who worked on the project. "But maybe it shouldn't have been." The theorists might have things all wrong. But it could also simply be that any population will have a few individuals that are way outside the average—humans who stand over 7 ft. tall, for example. They're very noticeable but not at all typical.

Until someone finds better evidence to the contrary, it's safe to assume that the very tiny galaxies filled with second-generation stars were by far the dominant type in the early cosmos. It would also have been safe to assume that nobody could spot them in their earliest incarnation without giant new telescopes—if not for Ellis. "He does like to push the frontiers," says theorist Norman with mixed amusement and respect. "It's always great fun to go to a meeting and see the latest Ellis most-distant-object sweepstakes entry."

EINSTEIN'S GIANT LENS

ORDINARILY, ELLIS EXPLAINS, YOU COULD never see small galaxies a mere 500 million years after the Big Bang; they're just too faint for any telescope now in existence. But the universe itself has supplied a way of boosting a telescope's magnifying power. The theory of relativity says massive objects warp the space around them, diverting light rays from their original path. In the 1930s Albert Einstein realized this meant a star, say, could act as a lens, distorting and amplifying the light from something behind it. In practice, he said, it probably happens so rarely that we will never see it.



THOMAS MICHAEL ALLEMAN FOR TIME

REMOTE CONTROL
Stark, left, and Ellis, in a Caltech control room, study images beamed from a telescope in Hawaii

Einstein was wrong. So-called gravitational lenses have become a major factor in modern astronomy. They have revealed, among other things, the existence of tiny planets around stars thousands of light-years away and have created weird optical effects, including multiple images of faraway quasars. If you look at a massive cluster of galaxies, Ellis figured, you might see amplified images of more distant galaxies, too faint to be seen otherwise. So a year or two ago, he started aiming the Keck at galactic clusters, and along with Stark, he identified six candidate objects. To make certain that these were truly far away, the pair has come back to the Keck for a second, more intensive look. "We want to be absolutely sure we aren't fooling ourselves," says Ellis. "Before we claim we've really found them."

For an hour or so, it looked as though they wouldn't get the chance. They had just this one night at the Keck; the telescope is so overbooked that even an eminent astronomer like Ellis has to wait his turn, and his next observing run isn't until January 2007. But the engineers this night have figured out the problem. When Stark entered his user name in the online telescope log, he made a typo. Every time the focusing routine came upon it, the program froze. The typo has now been corrected. The Keck can focus again, and to their delight, Stark and Ellis are able to confirm that at least three of their faint galaxies do seem to lie hundreds of millions of light-years farther away—and hundreds of millions of years closer to the Big Bang—than anything ever seen before.

"It's regrettable that we couldn't check the other three," Ellis says a few days later, "but we're now very confident and very excited. If we've found this many in such a tiny area of the sky, there could be enough of these small galaxies to supply a substantial fraction of the energy that reionized the universe. I'm very confident that we have an important result."

If anything, that's an understatement. The first galaxies to emerge from the blackness of the early universe can't be studied in detail until telescope technology makes another great leap. But Ellis and Stark may have got a glimpse—and given theorists the first hard evidence—of that unimaginably distant time when the cosmos left infancy behind and entered the formative childhood that led, eventually, to our sun and the tiny blue planet that circles it. ■

> "It's always great fun to see the latest Richard Ellis entry in the most-distant-object sweepstakes."
> —**MIKE NORMAN**, University of California at San Diego