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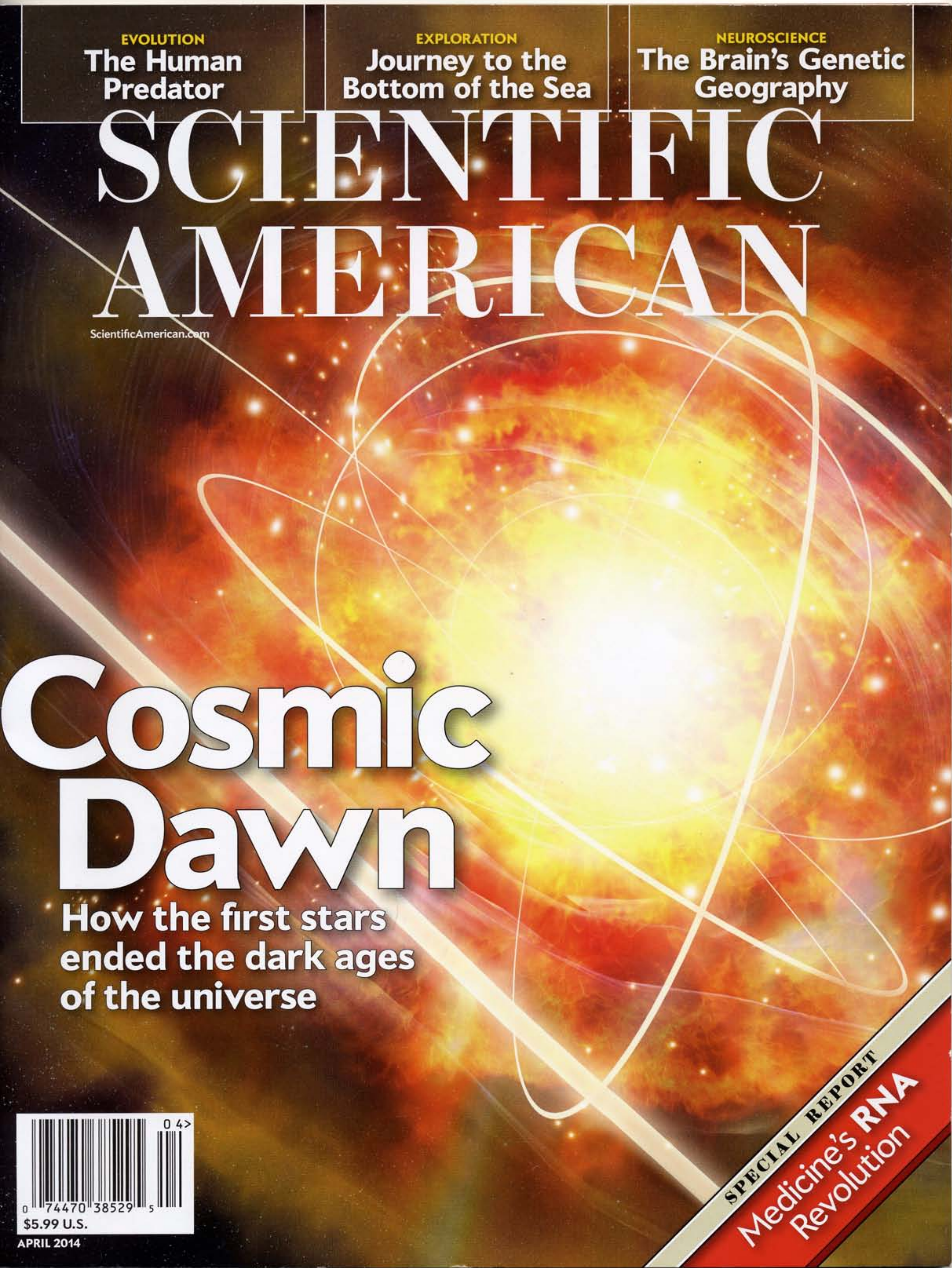

Cosmic Dawn

How the first stars ended the dark ages of the universe

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Not long after the big bang's flash, all light left

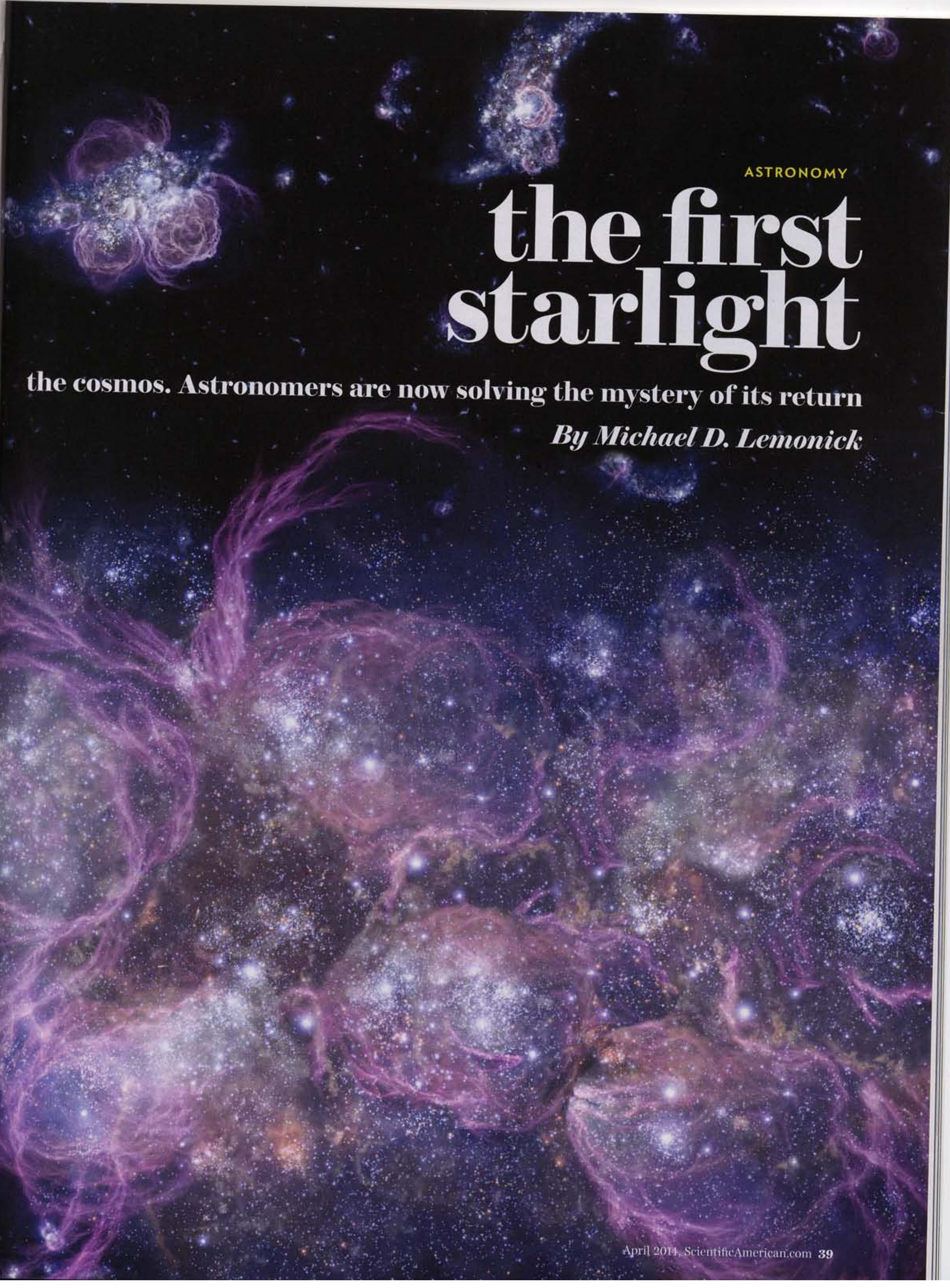
FIRST STARS in the universe were unimaginably large—perhaps a million times the mass of our sun. They would have helped clear the fog enshrouding the early universe before dying in supernova explosions, seen here in an artist's impression.

ASTRONOMY

the first starlight

the cosmos. Astronomers are now solving the mystery of its return

By Michael D. Lemonick



Michael D. Lemonick is a writer at Climate Central, a nonprofit news site, and author of *Mirror Earth: The Search for Our Planet's Twin* (Walker Books, 2012). For 21 years he was a science writer for *Time* magazine.

ABOUT 13.8 BILLION YEARS AGO, just 400,000 years or so after the big bang, the universe abruptly went dark.

Before that time, the entire visible universe was a hot, seething, roiling plasma—a dense cloud of protons, neutrons and electrons. If anyone had been there to see it, the universe would have looked like a pea soup fog, but blindingly bright.

Around the 400,000-year mark, however, the expanding universe cooled enough for hydrogen atoms to form at last—an event known as recombination. The fog lifted, the universe continued to cool and everything quickly faded to black. After the unimaginable brilliance of the big bang and its immediate aftermath, the cosmos entered what astronomers call the dark ages of the universe.

And dark they were. For even when the first stars started to ignite, their light shone brightest in the ultraviolet portion of the spectrum—just the kind of light that the newly formed hydrogen gas tends to absorb. The universe traded its primordial hot, bright fog for one that was cool and dark.

Eventually this fog would lift, but how it did so is a question that has long baffled astronomers. Maybe it was accomplished by the first stars, whose intense light gradually but relentlessly broke the hydrogen apart in a process called reionization. Perhaps instead the energy for reionization came from the radiation that is generated by hot gas spiraling into giant black holes.

The key to figuring out how and when reionization took place, unsurprisingly, is finding the oldest objects in the universe and trying to tease out their nature and their origins. When did the first stars turn on, and what were they like? How did individual stars assemble themselves into galaxies, and how did those galaxies form the supermassive black holes that lie at the core of nearly all of them? At what point in this progression from stars to galaxies to black holes did reionization take place? And was the process gradual or abrupt?

Astrophysicists have been asking many of these questions since the 1960s. Only recently, however, have telescopes and computer models gotten powerful enough to offer some answers: the latter by simulating the emergence and evolution of the first stars in the universe, and the former by gathering telltale glimmers of light from less than half a billion years after the big bang—a time when the first galaxies were in their infancy.

SUPERSTARS

A DECADE OR SO AGO astronomers believed that they had a good handle on how the first generation of stars came to be. Immediately after recombination, the hydrogen atoms that filled the cosmos were spread uniformly through space. In contrast, dark matter, which physicists believe to be made of invisible particles that have not yet been identified, had already begun clumping together in clouds known as halos, averaging somewhere between 100,000 and one million solar masses. Gravity from these halos sucked in the hydrogen. As the gas became increasingly concentrated and heated up, it flared into light, creating the first stars in the universe.

In principle, this first generation of giant stars, known to astronomers as Population III stars, could have broken up the veil of hydrogen gas and reionized the universe. But much

IN BRIEF

The universe's very first stars and galaxies were not like the objects we see today. Astronomers are reaching back in time to probe how the first objects in the universe came to be.

They are particularly interested in what caused the so-called reionization of the universe, when the neutral hydrogen atoms pervading the cosmos were broken up by light.

Observations and computer simulations suggest that the objects driving reionization could be million-solar-mass stars or the gaseous belches of enormous black holes.

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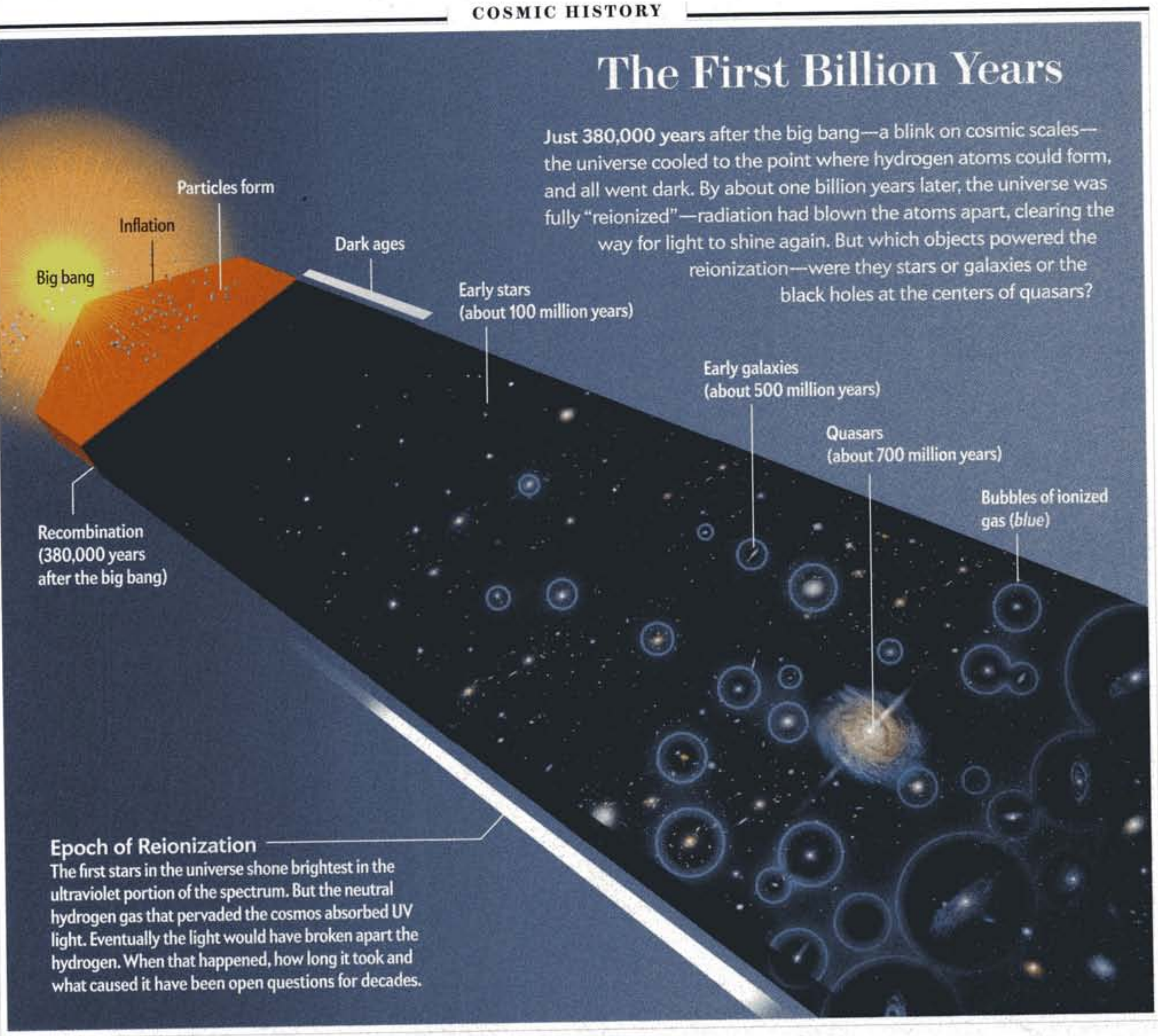


depends on the exact characteristics of these stars. If they were not bright enough or did not live long enough, they would not be capable of finishing the job.

The characteristics of these stars depend strongly on their size. As of a decade ago, astronomers believed that they would be uniformly gigantic, each with roughly 100 times the mass of the sun [*see box on next page*]. The reason: As a clump of gas tries to collapse under gravity, it heats up. The heat creates so-called radiation pressure that opposes gravity; unless the star can shed some of this heat, the collapse will stall.

The first stars were made mostly of hydrogen, which is relatively terrible at shedding heat. (Stars like our sun also have small but critical traces of elements such as oxygen and carbon, which help them to cool.) As a result, a protostar in the early universe would continue to accumulate hydrogen gas, but the high pressure would prevent it from forming a dense core that would burst into a fusion reaction—one that drives much of the surrounding gas back out into space. The star would just gorge itself on more and more gas until it built a massive, diffuse core.

Now, however, says Thomas Greif, a Harvard University postdoctoral fellow who creates some of the most sophisticated simulations of early star formation, "things look a bit more complicated." These newest simulations include not just gravity but also equations describing the feedbacks generated by increasingly pressurized hydrogen as the gas collapses. It turns out that the collapse of a hydrogen cloud can play out in many different ways. In some cases, the first stars could have been up to a *million* times as massive as the sun. In others, the collapsing cloud would have fragmented, creating several stars of just a few tens of solar masses.

These size differences imply huge variations in the possible lifetimes of the first stars—and therefore in when reionization might have occurred. Giant stars of 100 solar masses or more are the rock 'n' rollers of astronomy: they live fast and die young. Smaller stars would churn through their nuclear fuel more slowly, implying that if stars were responsible for reionization, the process would have been a long-drawn-out one, spanning many hundreds of millions of years.

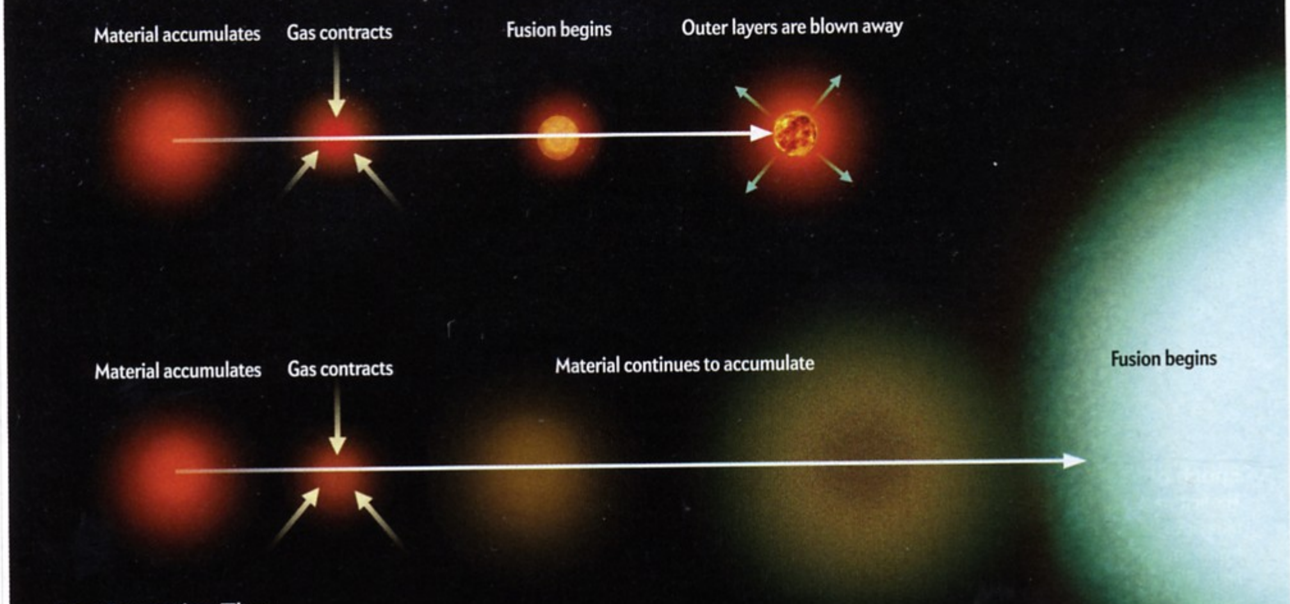
Illustrations by Moonrunner Design

Young Giants of the Universe

Why were the first stars so large? All stars execute a cosmic balancing act—gravity attempts to squeeze them as tight as possible, but the gas pressure inside the star fights against gravity and keeps the star inflated. By comparing star formation in the modern universe with star formation in the early universe, we can begin to understand why the universe's first stars were so massive.

Star Formation Now

Modern galaxies are littered with ingredients such as carbon, oxygen and dust. These materials help gases to cool. Cool clouds have lower pressures. Lower pressure means a collapsing cloud of dust can contract until its core is extremely dense—dense enough to get the hydrogen in its center to undergo thermonuclear fusion. After fusion begins, the sudden burst of energy blows away the outermost layers of the collapsing cloud, leaving a relatively small star behind.



Star Formation Then

The early universe did not have any carbon, oxygen or dust—only hydrogen, with a smattering of helium and lithium. Hydrogen does not cool very efficiently. As gas clouds began to collapse, the hot hydrogen kept the density in early protostars low. Without enough density to initiate fusion, the gas clouds continued to accumulate more and more gas—anywhere from 100 to one million suns' worth. Only then would they get hot and dense enough to initiate fusion.

BLACK LIGHTS

HOWEVER LARGE THEY WERE, all these stars would have ended their existence in fiery supernovae before collapsing into black holes. And these black holes—perhaps more than the stars from which they came—may have fueled the engine of reionization.

Black holes swallow nearby gas voraciously, and as the gas falls in, it is compressed and heated to temperatures of millions of degrees. It is so hot that while most of the gas eventually disappears into the black hole, some spews back out into space in the form of jets, which shine so brightly that the light can be seen halfway across the cosmos. We call these beacons quasars.

From the 1960s through the 1990s, quasars were really the only way to probe the early universe. At first, astronomers had no clue what they were. Quasars looked like nearby stars but had huge redshifts—a reddening of their light caused by the expansion of the universe. The impressive redshifts indicated that quasars were vastly farther away than any stand-alone star could possibly be and were thus vastly brighter as well. The first one ever found, 3C 273, had a redshift of 0.16, indicating that its light had begun traveling about two billion years ago.

"Then, very quickly," says Princeton University astrophysicist Michael A. Strauss, "people found quasars up to redshift 2"—a look-back time of more than 10 billion years. By 1991 Maarten Schmidt, James E. Gunn and Donald P. Schneider, working together at Palomar Observatory in California, had found a quasar with a redshift of 4.9, dating to 12.5 billion years before the present, or just a billion years and change after the big bang.

Yet analyses of the redshift 4.9 quasar found no evidence that its light was being absorbed by neutral hydrogen. Apparently the universe had already been reionized by the time the light from this quasar had begun its journey to Earth.

For most of the 1990s, no one was able to find a quasar any farther away than this one. The failure was not for a lack of powerful instruments—both the Hubble Space Telescope and the Keck telescopes at Mauna Kea in Hawaii came online in the early 1990s, significantly increasing astronomers' ability to see deep into the universe—but because quasars are rare to begin with. They erupt only from the most massive of supermassive black holes. And from our perspective, they do not shine unless their jets of gas happen to be aimed directly at us.

Moreover, those jets blast into existence only when a black hole is actively swallowing gas. For most black holes, that kind of activity peaked between a redshift of 2 and 3, when galaxies were more gas-rich, on average, than they are today. If you look further out than that sweet spot in cosmic time, the number of quasars drops off rapidly.

It was not until 2000, when the Sloan Digital Sky Survey began methodically searching across an enormous swath of sky with the largest digital detectors ever built until that point, that the record was shattered in earnest (the detectors were designed by the same Gunn). "The Sloan was just fabulously successful in finding distant quasars," says California Institute of Technology astronomer Richard Ellis. "They found something like 40 or 50 quasars beyond a redshift of 5.5."

But the survey could not reach back much further than a handful of quasars that it found between redshift 6 and 6.4, and even at that distance there was no sign of neutral hydrogen. It was only with the discovery of a quasar at redshift 7.085, by the UKIRT Infrared Deep Sky Survey at Mauna Kea, that astronomers found small but significant amounts of ultraviolet-absorbing hydrogen obscuring the object's light. This quasar, known as ULAS J1120+0641, shining about 770 million years after the big bang, finally let astrophysicists dip a toe into the era of cosmic reionization—but just a toe because even this close to the big bang, most of the neutral hydrogen had already been destroyed.

Or maybe not. It's possible that this quasar sits in an unusually sparse region of leftover neutral hydrogen and that most other quasars at this distance would have been more completely shrouded. It is equally possible that ULAS J1120+0641 is in an especially dense region; maybe reionization was already complete pretty much everywhere else. Without more examples, astronomers cannot be sure, and the prospects of finding enough quasars at this distance to do a robust statistical study are slim.

ULAS J1120+0641 has plenty to tell astronomers anyway. For one thing, Ellis says, "the number of quasars is falling so steeply with distance that it's inconceivable that massive black holes are a major source of radiation that reionizes the universe." For another, the black hole that powers this particular quasar must have a billion suns' worth of mass in order to generate the amount of energy that makes it visible from so far away. "It's almost impossible to understand how it could have formed in the limited time that the universe had up to that point," Ellis says.

Yet form it did. Abraham Loeb, chair of Harvard's astronomy department, points out that if a first-generation star with 100 solar masses collapsed into a black hole a couple of hundred million years after the big bang, it could conceivably have grown to quasar proportions in the available time if conditions were just right. "But you would need to feed the black hole continuously," he says, and it is hard to imagine how you could do that. "They shine so brightly, they produce so much energy, that they expel the gas out of their vicinity." Without a nearby supply of gas, the quasar goes temporarily dark, allowing gas to accumulate again until it can flare back into life—and blow away its fuel supply once more. "So there is always the notion of a duty cycle," Loeb says. "The black hole is able to grow only for a fraction of the time."

Yet, he says, black holes can also grow by merging with one another, which would accelerate their growth process. In addition, the recent work on star sizes implies that those first black holes may have formed not from stars that were 100 solar masses, but one million solar masses, a suggestion Loeb first put forth in a 2003 paper that he co-authored. "This has become a popular idea," he says, buttressed by simulations such as Greif's. "And because these stars would shine as brightly as the entire Milky Way, you could, in principle, see them with the James Webb Space Telescope," the massive successor to the Hubble telescope that is currently scheduled to launch in 2018.

GALAXY QUEST

EVEN AS THE HUNT for distant quasars has more or less petered out, the search for galaxies closer and closer to the big bang has taken off. Perhaps the most important triggering event was an image called the Hubble Deep Field. It was made in 1995, when Robert Williams, then director of the Space Telescope Science Institute, used a perk of the office known as "director's discretionary time" to aim Hubble at an evidently blank patch of sky and let it stare for a cumulative 30 hours or so to pick up whatever faint objects might be there. "Some very serious astronomers told him it was a waste of time," recalls current director Matt Mountain, "that he wouldn't see anything."

In fact, the telescope picked up several thousand small, faint galaxies, many of which turned out to be among the most distant ever seen. Follow-up Deep Field images—made with Hubble's new, infrared-sensitive Wide Field Camera 3, which was installed during a 2009 servicing mission and is some 35 times more effective than its predecessor—have found even more. "We've gone from four or five galaxies with a redshift of 7 or more," says University of Arizona observer Daniel Stark, Ellis's longtime collaborator, "to more than 100." One of these, described by Ellis, Stark and several co-authors in a 2012 paper, appears to be at a redshift of no less than 11.9, fewer than 400 million years after the big bang.

Like the record-holding quasar, these young galaxies can tell astronomers plenty about the distribution of intergalactic hydrogen at the time. When observers look at their output of ultraviolet light, a significant fraction of what they would expect to see is missing, absorbed by neutral hydrogen that surrounds them. That fraction drops gradually as they look at galaxies that are further from the big bang—until, at about a billion years after the universe was born, the cosmos is fully transparent.

In short, not only did galaxies exist to provide a source for the ionizing radiation, they also reveal how the universe made the transition from neutral to fully ionized. Astronomical detectives have a smoking gun, and they have a victim. There is a catch, however. If you take the 100-odd galaxies found so far above a redshift of 7 and extrapolate across the entire sky, you do not have enough total ultraviolet radiation to ionize all the neutral hydrogen. The gun does not seem to be powerful enough to do the job. The required energy cannot come from black holes, either, given how hard it is to make enough supermassive black holes quickly enough to do so.

Yet the answer may be relatively straightforward. Faint as they seem to us, the galaxies we are able to see at the very edge of Hubble's vision are presumably the brightest of their epoch. There must be many more galaxies at that distance that are simply too dim to see with any existing telescope. If you make that reasonable assumption, Ellis says, "I think most people now believe that galaxies do most of the work in reionizing the universe."

THE EINSTEIN CARD

AS FOR WHAT TRULY NEWBORN GALAXIES look like and when they first turned on, "we're not there yet," Stark admits. "The galaxies we do see are fairly small, and they look much younger than galaxies that have been studied in detail one billion to two billion years later." But they already have as many as 100 million stars, and the mix of their colors (after you correct for the fact that their light is redshifted) suggests their stars are on average redder than you would expect in a very young galaxy. "These objects," Stark says, "look like they've been forming stars for at least 100 million years already. Hubble has taken us close to the precipice, to where we'll see the first generation of stars, but it will take the James Webb Space Telescope to get us there."

Hubble has not exhausted its options, however. The telescope itself can see only to a certain faintness limit without taking absurdly long exposures. Yet the universe has supplied its own natural lenses that can boost Hubble's power. These so-called gravitational lenses take advantage of the fact that massive objects—in this case, clusters of galaxies—warp the space around them, distorting and sometimes magnifying the objects that lie far beyond.

It's almost impossible to understand how the black hole could have grown so large in the limited time that the universe had up to that point. Yet form it did.

In particular, says observer Marc Postman of the Space Telescope Science Institute, "we get a big amplification of any very distant galaxies that lie behind those clusters. They can be 10 or 20 times brighter than comparable unlensed galaxies." Postman is principal investigator for the Cluster Lensing and Supernova Survey with Hubble, a program that has used the technique to identify some 250 additional galaxies between redshift 6 and 8 and a handful more that may go up to redshift 11. From what they have seen so far, the results are consistent with those coming out of the various Deep Field surveys.

Now Hubble is going deeper still: Mountain has devoted some of his own director's discretionary time to a new project called Frontier Fields, in which observers will look for magnified images of faint, distant galaxies that lie behind six especially massive and powerful clusters. Over the next three years, says Jennifer Lotz, the project's lead observer, "we're going to look at each of them for something like 140 orbits of Hubble [each orbit is about 45 minutes' worth of observing time], which will let us probe deeper into the universe than anything we've ever seen."

BURST SEARCH

YET ANOTHER KIND OF COSMIC BEACON, meanwhile, could ultimately prove to be an even better probe of the early universe. When first discovered in the 1960s, gamma-ray bursts—short blasts of high-frequency radiation that pop up in random directions—were an utter mystery. Nowadays astronomers believe that many of them come from the deaths of very massive stars: as the stars collapse to form black holes, they spew jets of gamma rays out into space. When the jets slam into the surrounding clouds of gas, they trigger a secondary, bright afterglow of visible and infrared light that can be seen by conventional telescopes.

Here is how the observations work: When the orbiting Swift Gamma-Ray Burst observatory detects a gamma-ray flash, it swivels to point its onboard telescopes at the spot. At the same time, it beams the location's coordinates to ground-based observers. If their telescopes get there before the flash fades, astronomers can measure the afterglow's redshift and thus the redshift—and age—of the galaxy where the burst went off.

What makes the technique so valuable is that gamma-ray bursts make other cosmic objects look positively feeble. "For the first few hours," says Edo Berger, a Harvard astrophysicist who specializes in the bursts, "they probably outshine galaxies by a factor of a million, and they're 10 to 100 times brighter than quasars." You do not need a long exposure with Hubble to see them. In 2009 a telescope on Mauna Kea reliably measured the redshift of one burst at 8.2, putting it at 600 million years after the big bang.

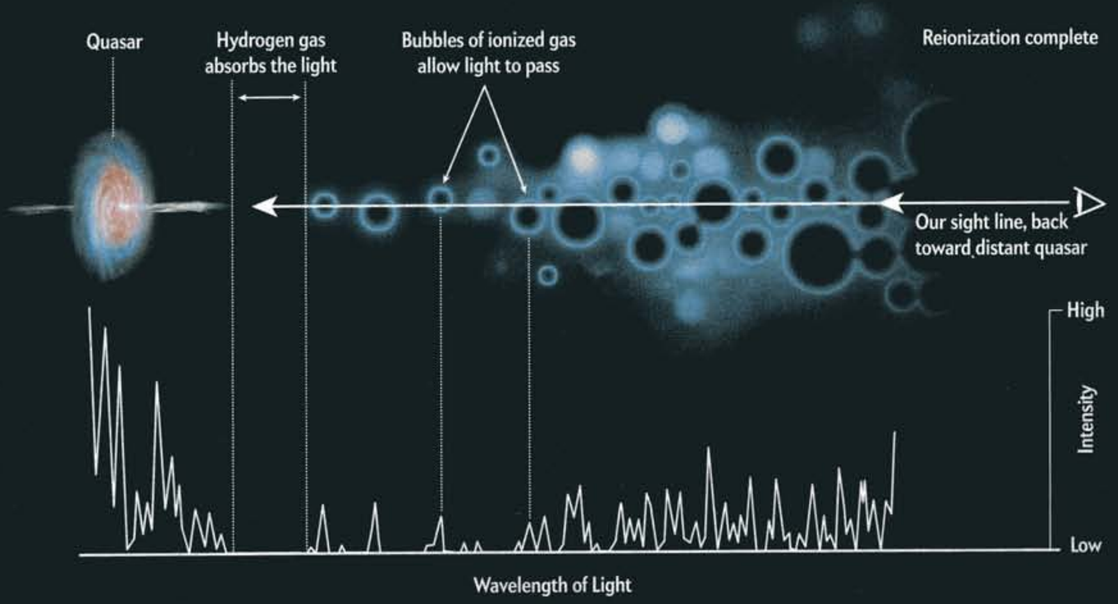
The flash was so bright, Berger says, that it could have been seen out to a redshift of 15 or even 20, which would be less than 200 million years after the big bang, close to the time the very first stars may have been shining. And it is entirely plausible, he says, that those very massive stars would be exactly the kind to produce gamma-ray bursts as they die. In fact, Berger says, there is reason to think these first-generation stars would create such energetic gamma-ray bursts that they would appear brighter than the ones discovered so far, even though they would be farther away.

Unlike quasars, moreover, which occur only in galaxies with supermassive black holes, and unlike the galaxies Hubble can see, which are the brightest tips of a grand galactic iceberg, gamma-ray bursts are just as powerful in tiny galaxies as they are in big ones. They provide, in other words, a much more representative sample of the universe at any given time.

The downside, Berger says: 99 percent of gamma-ray bursts are pointed away from Earth, and of the remaining one per day or so that are detected by satellites, only a minuscule fraction are at a high redshift. Gathering a representative sample of extremely high redshift bursts would therefore take a decade or more, and "Swift is probably not going to last" that long, Berger says. Ideally, he notes, someone should launch a successor satellite that could feed burst coordinates to the James Webb telescope or to the three 30-meter-class ground-based instruments

Quasar Quest

Quasars are among the brightest objects in the early universe, beacons that astronomers can spot from more than 10 billion light-years away. As light from the quasar travels through the universe toward our telescopes, two things happen: First, its light gets stretched along the way by the expansion of the universe. In addition, any atomic hydrogen gas will absorb some of the light. Astronomers can therefore plot the absorption of light by wavelength to see how the prevalence of hydrogen gas has changed over time. They have found that isolated bubbles of ionized gas grew larger and more frequent as the universe evolved.



SOURCE: GEORGE DJORGOVSKI *California Institute of Technology* AND ABRAHAM LOEB *Harvard University*

that are expected to be operating within the next decade. Proposals to do so have so far failed to get the go-ahead from either NASA or the European Space Agency.

In any case, once the James Webb telescope and the next generation of gigantic ground-based telescopes begin observations, quasar hunters, galaxy surveyors and those who search for the telltale afterglows of gamma-ray bursts in other electromagnetic wavelengths will be able to catalogue much older and fainter objects than they can today. Their work will help to nail down exactly what was going on in the very early universe.

Radio astronomers, meanwhile, will be looking to instruments such as the Murchison Widefield Array in Australia, the Precision Array for Probing the Epoch of Reionization in South Africa, the Square Kilometer Array, split between those two countries, and the Low Frequency Array (LOFAR), with antennas located in several European countries, to try mapping out slowly disappearing clouds of neutral hydrogen during the first billion years of cosmic history. The hydrogen itself emits radio waves, so in principle, astronomers will be able to look at those emissions at different epochs—each redshifted by a different amount, depending on how far away they are—and take snapshots of the hydrogen as it is gradually eaten away by high-energy radiation as the images come forward in time. And finally, astronomers will be using the Atacama Large Millimeter/submillimeter Array in the high Chilean desert to search for carbon monoxide and other molecules that mark the interstellar clouds where the second generation of stars was born.

When cosmologists first detected the leftover electromagnetic radiation from the big bang in 1965, it galvanized them to try and understand the life history of the universe from its birth right through to the present. They are not quite there yet. But there is every reason to believe that by 2025, the 60th anniversary of that discovery, the last remaining blanks will finally be filled in. ■

MORE TO EXPLORE

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