THE FIRST STARS IN THE UNIVERSE

Exceptionally massive and bright, the earliest stars changed the course of cosmic history

BY RICHARD B. LARSON AND VOLKER BROMM
ILLUSTRATIONS BY DON DIXON

We live in a universe that is full of bright objects. On a clear night one can see thousands of stars with the naked eye. These stars occupy merely a small nearby part of the Milky Way galaxy; telescopes reveal a much vaster realm that shines with the light from billions of galaxies. According to our current understanding of cosmology, however, the universe was featureless and dark for a long stretch of its early history. The first stars did not appear until perhaps 100 million years after the big bang, and nearly a billion years passed before galaxies proliferated across the cosmos. Astronomers have long wondered: How did this dramatic transition from darkness to light come about?

Updated from the December 2001 issue

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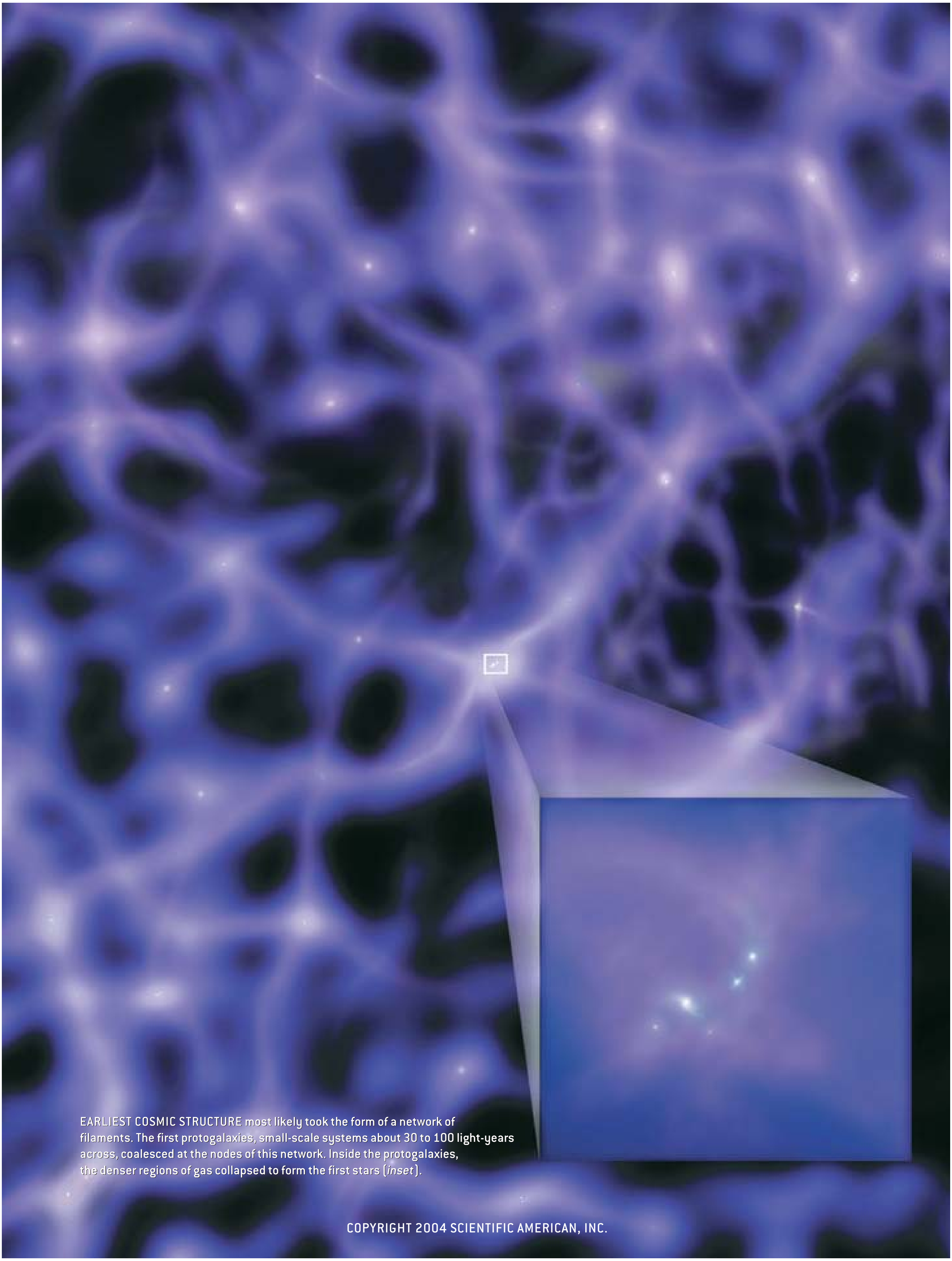

EARLIEST COSMIC STRUCTURE most likely took the form of a network of filaments. The first protogalaxies, small-scale systems about 30 to 100 light-years across, coalesced at the nodes of this network. Inside the protogalaxies, the denser regions of gas collapsed to form the first stars (*inset*).

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After decades of study, researchers have recently made great strides toward answering this question. Using sophisticated computer simulation techniques, cosmologists have devised models that show how the density fluctuations left over from the big bang could have evolved into the first stars. In addition, observations of distant quasars have allowed scientists to probe back in time and catch a glimpse of the final days of the "cosmic dark ages."

The new models indicate that the first stars were most likely quite massive and luminous and that their formation was an epochal event that fundamentally changed the universe and its subsequent evolution. These stars altered the dynamics of the cosmos by heating and ionizing the surrounding gases. The earliest stars also produced and dispersed the first heavy elements, paving the way for the eventual formation of solar systems like our own. And the collapse of some of the first stars may have seeded the growth of supermassive black holes that formed in the hearts of galaxies and became the spectacular power sources of quasars. In short, the earliest stars made possible the emergence of the universe that we see today—everything from galaxies and quasars to planets and people.

The Dark Ages

THE STUDY of the early universe is hampered by a lack of direct observations. Astronomers have been able to examine much of the universe's history by training their telescopes on distant galaxies and quasars that emitted their light billions of years ago. The age of each object can be determined by the redshift of its light, which shows how much the universe has expanded since the light was produced. The oldest galaxies and quasars that have been observed so far date from about a billion years after the big bang (assuming a present age for the universe of 13.7 billion years). Researchers will need better telescopes to see more distant objects dating from still earlier times.

Cosmologists, however, can make deductions about the early universe based on the cosmic microwave background radiation, which was emitted about 400,000 years after the big bang. The uniformity of this radiation indicates that matter was distributed very smoothly at that time. Because there were no large luminous objects to disturb the primordial soup, it must have remained smooth and featureless for millions of years afterward. As the cosmos expanded, the background radiation redshifted to longer wavelengths and the universe grew increasingly cold and dark. Astronomers have no observations of this dark era. But by a billion years after the big bang, some bright galaxies and quasars had already appeared, so the first stars must have formed sometime before. When did these first luminous objects arise, and how might they have formed?

Many astrophysicists, including Martin Rees of the University of Cambridge and Abraham Loeb of Harvard University, have made important contributions toward solving these problems. The recent studies begin with the standard cosmological models that describe the evolution of the universe following the big bang. Although the early universe was remarkably smooth, the background radiation shows evidence of small-scale density fluctuations—clumps in the primordial soup. These clumps would gradually evolve into gravitationally bound structures. Smaller systems would form first and then merge into larger agglomerations. The denser regions would take the form of a network of filaments, and the first star-forming systems—small protogalaxies—would coalesce at the nodes of this network. In a similar way, the protogalaxies would then merge to form galaxies, and the galaxies would congregate into galaxy clusters. The process is ongoing: although galaxy formation is now mostly complete, galaxies are still assembling into clusters, which are in turn aggregating into a vast filamentary network that stretches across the universe.

According to the models, the first small systems capable of forming stars should have appeared between 100 million and 250 million years after the big bang. These protogalaxies would have been 100,000 to one million times more massive than the sun and would have measured 30 to 100 light-years across. These properties are similar to those of

It seems safe to conclude that the FIRST STARS IN THE UNIVERSE WERE TYPICALLY MANY TIMES more massive and luminous than the sun.

Overview/*The First Stars*

- Computer simulations show that the first stars should have appeared between 100 million and 250 million years after the big bang. They formed in small protogalaxies that evolved from density fluctuations in the early universe.
- Because the protogalaxies contained virtually no elements besides hydrogen and helium, the physics of star formation favored the creation of bodies that were many times more massive and luminous than the sun.
- Radiation from the earliest stars ionized the surrounding hydrogen gas. Some stars exploded as supernovae, dispersing heavy elements throughout the universe. The most massive stars collapsed into black holes. As protogalaxies merged to form galaxies, the black holes possibly became concentrated in the galactic centers.

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the molecular gas clouds in which stars are currently forming in the Milky Way, but the first protogalaxies would have differed in fundamental ways. For one, they would have consisted mostly of dark matter, the putative elementary particles that are believed to make up 90 percent of the universe's mass. In present-day large galaxies, dark matter is segregated from ordinary matter: over time, ordinary matter concentrates in the galaxy's inner region, whereas the dark matter remains scattered throughout an enormous outer halo. But in the protogalaxies, the ordinary matter would still have been mixed with the dark matter.

The second important difference is that the protogalaxies would have contained no significant amounts of any elements besides hydrogen and helium. The big bang produced hydrogen and helium, but most of the heavier elements are created only by the thermonuclear fusion reactions in stars, so they would not have been present before the first stars had formed. Astronomers use the term "metals" for all these heavier elements. The young metal-rich stars in the Milky Way are called Population I stars, and the old metal-poor stars are called Population II stars. The stars with no metals at all—the very first generation—are sometimes called Population III stars.

In the absence of metals, the physics of the first star-forming systems would have been much simpler than that of present-day molecular gas clouds. Furthermore, the cosmological models can provide, in principle, a complete description of the initial conditions that preceded the first generation of stars. In contrast, the stars that arise from molecular gas clouds are born in complex environments that have been altered by the effects of previous star formation. Several research groups have used computer simulations to portray the formation of the earliest stars.

A team consisting of Tom Abel, Greg Bryan and Michael L. Norman (now at Pennsylvania State University, Columbia University and the University of California at San Diego, respectively) has made the most realistic simulations. In collaboration with Paolo Coppi of Yale University, we have done simulations based on simpler assumptions but intended to explore a wider range of possibilities. Toru Tsuribe, now at Osaka University in Japan, has made similar calculations using more powerful computers. The work of Fumitaka Nakamura and Masayuki Umemura (now at Niigata and Tsukuba universities in Japan, respectively) has yielded instructive results. All these studies have produced similar descriptions of how the earliest stars might have been born.

Let There Be Light!

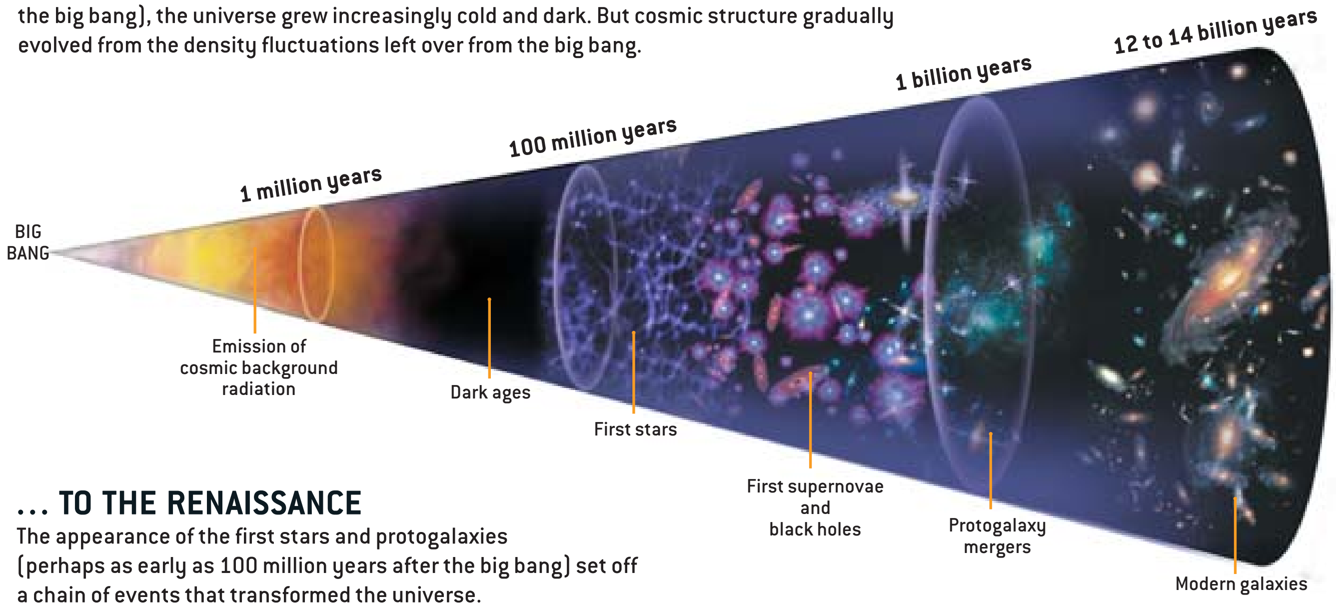
THE SIMULATIONS show that the primordial gas clouds would typically form at the nodes of a small-scale filamentary network and then begin to contract because of their gravity. Compression would heat the gas to temperatures above 1,000 kelvins. Some hydrogen atoms would pair up in the dense, hot gas, creating trace amounts of molecular hydrogen. The hydrogen molecules would then start to cool the densest parts of the gas by emitting infrared radiation after they collided with hydrogen atoms. The temperature in the densest parts would drop to 200 to 300 kelvins, reducing the gas pressure in these regions, allowing them to contract into gravitationally bound clumps.

This cooling plays an essential role in allowing the ordinary matter in the primordial system to separate from the dark matter. The cooling hydrogen would set-

COSMIC TIMELINE

FROM THE DARK AGES ...

After the emission of the cosmic microwave background radiation (about 400,000 years after the big bang), the universe grew increasingly cold and dark. But cosmic structure gradually evolved from the density fluctuations left over from the big bang.



... TO THE RENAISSANCE

The appearance of the first stars and protogalaxies (perhaps as early as 100 million years after the big bang) set off a chain of events that transformed the universe.

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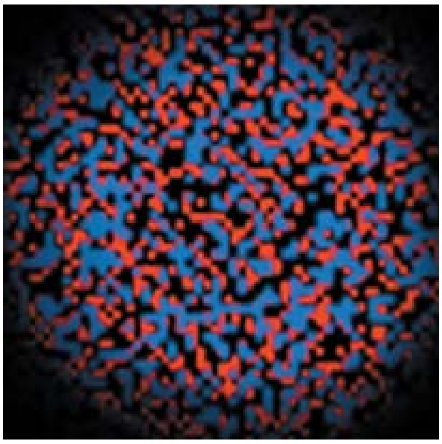
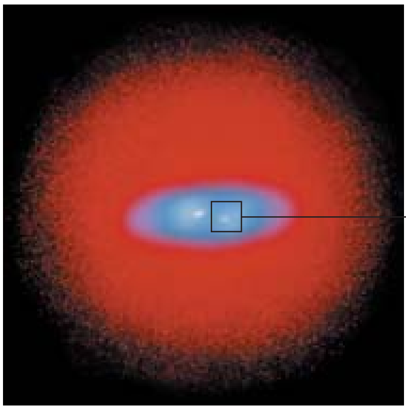
THE BIRTH AND DEATH OF THE FIRST STARS



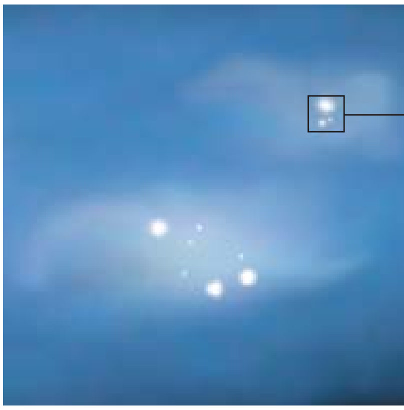
PRIMEVAL TURMOIL

The process that led to the creation of the first stars was very different from present-day star formation. But the violent deaths of some of these stars paved the way for the emergence of the universe that we see today.

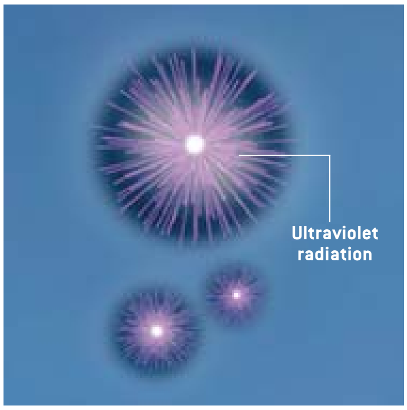
1 The first star-forming systems—small protogalaxies—consisted mostly of the elementary particles known as dark matter (*shown in red*). Ordinary matter—mainly hydrogen gas (*blue*)—was initially mixed with the dark matter.



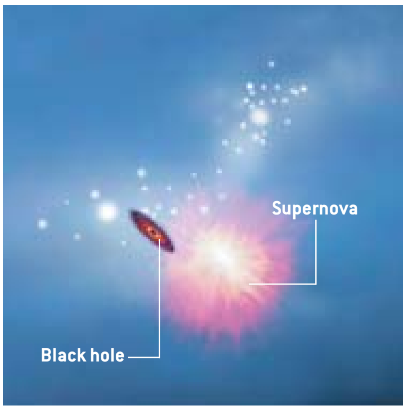
2 The cooling of the hydrogen allowed the ordinary matter to contract, whereas the dark matter remained dispersed. The hydrogen settled into a disk at the center of the protogalaxy.



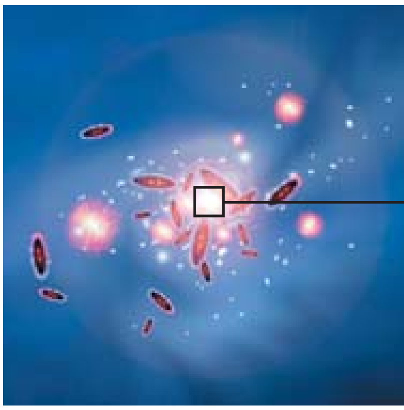
3 The denser regions of gas contracted into star-forming clumps, each hundreds of times as massive as the sun. Some of the clumps of gas collapsed to form very massive, luminous stars.



4 Ultraviolet radiation from the stars ionized the surrounding neutral hydrogen gas. As more and more stars formed, the bubbles of ionized gas merged and the intergalactic gas became ionized.



5 A few million years later, at the end of their brief lives, some of the first stars exploded as supernovae. The most massive stars collapsed into black holes.



6 Gravitational attraction pulled the protogalaxies toward one another. The collisions most likely triggered star formation, just as galactic mergers do now.

7 Black holes possibly merged to form a supermassive hole at the protogalaxy's center. Gas swirling into this hole might have generated quasarlike radiation.

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tle into a flattened rotating configuration that was clumpy and filamentary and possibly shaped like a disk. But because the dark-matter particles would not emit radiation or lose energy, they would remain scattered in the primordial cloud. Thus, the star-forming system would come to resemble a miniature galaxy, with a disk of ordinary matter and a halo of dark matter. Inside the disk, the densest clumps of gas would continue to contract, and eventually some of them would undergo a runaway collapse and become stars.

The first star-forming clumps were much warmer than the molecular gas clouds in which most stars currently form. Dust grains and molecules containing heavy elements cool the present-day clouds much more efficiently to temperatures of only about 10 kelvins. The minimum mass that a clump of gas must have to collapse under its gravity is called the Jeans mass, which is proportional to the square of the gas temperature and inversely proportional to the square root of the gas pressure. The first star-forming systems would have had pressures similar to those of present-day molecular clouds. But because the temperatures of the first collapsing gas clumps were almost 30 times higher, their Jeans mass would have been almost 1,000 times larger.

In molecular clouds in the nearby part of the Milky Way, the Jeans mass is roughly equal to the mass of the sun, and the masses of the prestellar clumps are about the same. If we scale up, we can estimate that the masses of the first star-forming clumps would have been 500 to 1,000 solar masses. The computer simulations mentioned above showed the formation of clumps with masses of several hundred solar masses or more.

Our group's calculations suggest that the predicted masses of the first star-forming clumps are not very sensitive to the assumed cosmological conditions. The predicted masses depend primarily on the physics of the hydrogen molecule and only secondarily on the cosmological model or simulation technique. One reason is that molecular hydrogen cannot cool the gas below 200 kelvins, making this a lower limit to the temperature of the first star-forming clumps. Another is that the cooling from molecular hydrogen becomes inefficient at the higher densities encountered when the clumps begin to collapse. At these densities the hydrogen molecules collide with other atoms before they have time to emit an infrared photon; this raises the gas temperature and slows the contraction until the clumps have built up to at least a few hundred solar masses.

Did the first collapsing clumps form stars with similarly large masses, or did they fragment and form many smaller stars? The research groups have pushed their calculations to the point at which the clumps are well on their way to forming stars, and none of the simulations has yet revealed any tendency for the clumps to fragment. This agrees with our understanding of present-day star formation; the fragmentation of clumps is typically limited to the formation of binary systems (two stars orbiting around each other). Fragmentation seems even less likely to occur in the primordial clumps, because the inefficiency of molecular hydrogen cooling would keep the Jeans mass high. The simulations, however, have not yet determined the final outcome of collapse with certainty, and the formation of binary systems cannot be ruled out.

Precise estimates of just how massive the first stars might have been are difficult because of feedback effects. In general, a star forms from the "inside out," by accreting gas from the surrounding clump onto a central protostellar core. But when does this accretion process shut off? As the star grows in mass, it produces intense radiation and matter outflows that may blow away some of the gas in the collapsing clump. Yet these effects depend strongly on the presence of heavy elements, and therefore they should be less important for the earlier stars. In collaboration with Loeb of Harvard, one of us (Bromm) has recently used numerical simulations to study the accretion onto a primordial protostar. The calculations show that a Population III star grows to roughly 50 solar masses within the first 10,000 years after the initial core forms. Although we could not follow the accretion further because of numerical limitations, it is likely that the star continues to grow, perhaps to 100 to 200 solar masses. It seems safe to conclude that the first stars were typically many times more massive and luminous than the sun.

The Cosmic Renaissance

WHAT EFFECTS did these first stars have on the rest of the universe? An important property of stars with no metals is that they have higher surface temperatures than stars with compositions like that of the sun. The production of nuclear energy at the center of a star is less efficient without metals, and the star would have to be hotter and more compact to produce enough energy to counteract gravity. Because of the more compact structure, the surface layers of the star would also be hotter. In collaboration with Loeb and Rolf-Peter Kudritzki of the University of Hawaii Institute for Astronomy, Bromm devised theoretical models of such stars with masses between 100 and 1,000 solar masses. The models showed that the stars had surface temperatures of 100,000 kelvins—about 17 times higher than the sun's surface temperature. Thus, the first starlight in the universe would have been mainly ultraviolet radiation from very hot stars, and it would have begun to heat and ionize the neutral hydrogen and helium gas around these stars soon after they formed.

We call this event the cosmic renaissance. Although astronomers cannot yet

THE AUTHORS

RICHARD B. LARSON and *VOLKER BROMM* have worked together to understand the processes that ended the "cosmic dark ages" and brought about the birth of the first stars. Larson, a professor of astronomy at Yale University, joined the faculty there in 1968 after receiving his Ph.D. from the California Institute of Technology. His research interests include the theory of star formation as well as the evolution of galaxies. Bromm earned his Ph.D. at Yale in 2000 and is now an assistant professor of astronomy at the University of Texas at Austin, where he focuses on the emergence of cosmic structure. The authors acknowledge the many contributions of Paolo Coppi, professor of astronomy at Yale, to their joint work on the formation of the first stars.

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STAR STATS

COMPARING CHARACTERISTICS

Computer simulations have given scientists some indication of the possible masses, sizes and other characteristics of the earliest stars. The lists below compare the best estimates for the first stars with those for the sun.

SUN

MASS: **1.989×10^{30} kilograms**
RADIUS: **696,000 kilometers**
LUMINOSITY: **3.85×10^{23} kilowatts**
SURFACE TEMPERATURE: **5,780 kelvins**
LIFETIME: **10 billion years**

FIRST STARS

MASS: **100 to 1,000 solar masses**
RADIUS: **4 to 14 solar radii**
LUMINOSITY: **1 million to 30 million solar units**
SURFACE TEMPERATURE: **100,000 to 110,000 kelvins**
LIFETIME: **3 million years**

estimate how much of the gas in the universe condensed into the first stars, even as little as one part in 100,000 could have been enough for these stars to ionize much of the remaining gas. Once the first stars started shining, a growing bubble of ionized gas would have formed around each one. As more and more stars formed over hundreds of millions of years, the bubbles of ionized gas would have merged, and the intergalactic gas would have become completely ionized.

Scientists from the California Institute of Technology and the Sloan Digital Sky Survey have found evidence for the final stages of this ionization process. They observed strong absorption of ultraviolet light in the spectra of quasars that date from about 900 million years after the big bang. The results suggest that the last patches of neutral hydrogen gas were being ionized at that time. A different probe has recently provided clues to the earliest stages of reionization, already occurring only 200 million years after the big bang. In an important breakthrough, NASA's Wilkinson Microwave Anisotropy Probe (WMAP) has measured the fundamental properties of the universe with high precision. These include the age of the universe—precisely 13.7 billion years—the proportions of dark and luminous matter, and dark energy in the cosmos. The biggest surprise: scrutinizing the subtle patterns that were imprinted into the photons of the cosmic microwave background, WMAP has indicated that ultraviolet radiation from the first stars ionized atomic hydrogen and helium, providing an abundance of free electrons early in cosmic history. Microwave background photons were polarized as they interacted with these electrons. An early generation of massive Population III stars seems to be required to account for the surprising strength of the polarization patterns.

Helium requires more energy to ionize than hydrogen does, but if the first stars were as massive as predicted, they would have ionized helium at the same time. On the other hand, if the first stars were not quite so massive, the helium must have been ionized later by energetic radiation from sources such as quasars. Future observations of distant objects may help determine when the universe's helium was ionized.

If the first stars were indeed very massive, they would also have had relatively short lifetimes—only a few million years. Some of the stars would have exploded as supernovae, expelling the metals they produced. Stars that are between 100 and 250 times as massive as the sun are predicted to blow up completely in energetic explosions, and some of the first stars most likely had masses in this range. Because metals are much more effective than hydrogen in cooling star-forming clouds and allowing them to collapse into stars, the production and dispersal of even a small amount could have had a major effect on star formation.

Working in collaboration with An-

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drea Ferrara of the Astrophysical Observatory of Arcetri in Italy, we have found that when the abundance of metals in star-forming clouds rises above one thousandth of the metal abundance in the sun, the metals rapidly cool the gas to the temperature of the cosmic background radiation. (This temperature declines as the universe expands, falling to 19 kelvins one billion years after the big bang and to 2.7 kelvins today.) This efficient cooling allows the formation of stars with smaller masses and may also considerably boost the rate at which stars are born. It is possible that the pace of star formation did not accelerate until after the first metals had been produced. In this case, the second-generation stars might have been the ones primarily responsible for lighting up the universe and bringing about the cosmic renaissance.

At the start of this active period of star birth, the cosmic background temperature would have been higher than in present-day molecular clouds (10 kelvins). Until the temperature dropped to that level—which happened about two billion years after the big bang—the process of star formation may still have favored massive stars. As a result, many such stars may have formed during the early stages of galaxy building by successive mergers of protogalaxies. A similar phenomenon may occur in the modern universe when two galaxies collide and trigger a starburst—a sudden increase in the rate of star formation—producing relatively large numbers of massive stars.

Puzzling Evidence

THIS HYPOTHESIS about early star formation might help explain some puzzling features of the present universe. One unsolved problem is that galaxies contain fewer metal-poor stars than would be expected if metals were produced at a rate proportional to the star formation rate. This discrepancy might be resolved if early star formation had produced relatively more massive stars; on dying, these stars would have dispersed large amounts of metals, which would have then been incorporated into most of the low-mass stars that we now see.

Another puzzling feature is the high metal abundance of the hot x-ray-emitting intergalactic gas in clusters of galaxies. This observation could be accounted for most easily if there had been an early period of rapid formation of massive stars and a correspondingly high supernova rate that chemically enriched the intergalactic gas. This case also dovetails with the recent evidence suggesting that most of the ordinary matter and metals in the universe lies in the diffuse intergalactic medium rather than in galaxies. To produce such a distribution of matter, galaxy formation must have been a spectacular process, involving intense bursts of massive star formation and barrages of supernovae that expelled most of the gas and metals out of the galaxies.

Stars that are more than 250 times more massive than the sun do not explode at the end of their lives; instead they collapse into massive black holes. Several of the simulations mentioned above predict that some of the first stars would have had masses this great. Because the first stars formed in the densest parts of the universe, any black holes resulting from their collapse would have become incorporated, via successive mergers, into systems of larger and larger size. It is possible that some of these black holes became concentrated in the inner part of large galaxies and seeded the growth of the supermassive black holes that are now found in galactic nuclei.

Furthermore, astronomers believe that the energy source for quasars is the gas whirling into the black holes at the centers of large galaxies. If smaller black holes had formed at the centers of some of the first protogalaxies, the accretion of matter into the holes might have generated "mini quasars." Because these objects could have appeared soon after the first stars, they might have provided an additional source of light and ionizing radiation at early times.

Thus, a coherent picture of the universe's early history is emerging, although certain parts remain speculative. The formation of the first stars and protogalaxies began a process of cosmic evolution. Much evidence suggests that the period of most intense star formation, galaxy building and quasar activity occurred a few billion years after the big bang and that all these phenomena have continued at declining rates as the universe has aged. Most of the cosmic structure building has now shifted to larger scales as galaxies assemble into clusters.

In the coming years, researchers hope to learn more about the early stages of the story, when structures started developing on the smallest scales. Because the first stars were most likely very massive and bright, instruments such as the James Webb Space Telescope—the planned successor to the Hubble Space Telescope—might detect some of these ancient bodies. Then astronomers may be able to observe directly how a dark, featureless universe formed the brilliant panoply of objects that now give us light and life. SA

The formation of the first stars and protogalaxies BEGAN A PROCESS OF COSMIC EVOLUTION.

MORE TO EXPLORE

Before the Beginning: Our Universe and Others. Martin J. Rees. Perseus Books, 1998.

The First Sources of Light. Volker Bromm in *Publications of the Astronomical Society of the Pacific,* Vol. 116, pages 103–114; February 2004. Available at **www.arxiv.org/abs/astro-ph/0311292**

The First Stars. Volker Bromm and Richard B. Larson in *Annual Reviews of Astronomy and Astrophysics,* Vol. 42, pages 79–118; September 2004. Available at **www.arxiv.org/abs/astro-ph/0311019**

Graphics from computer simulations of the formation of the first luminous objects can be found at **http://cfa-www.harvard.edu/~vbromm/**

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