Exploring Our Universe and Others

by Martin Rees

In the 21st century cosmologists will unravel the mystery of our universe's birth—and perhaps prove the existence of other universes as well

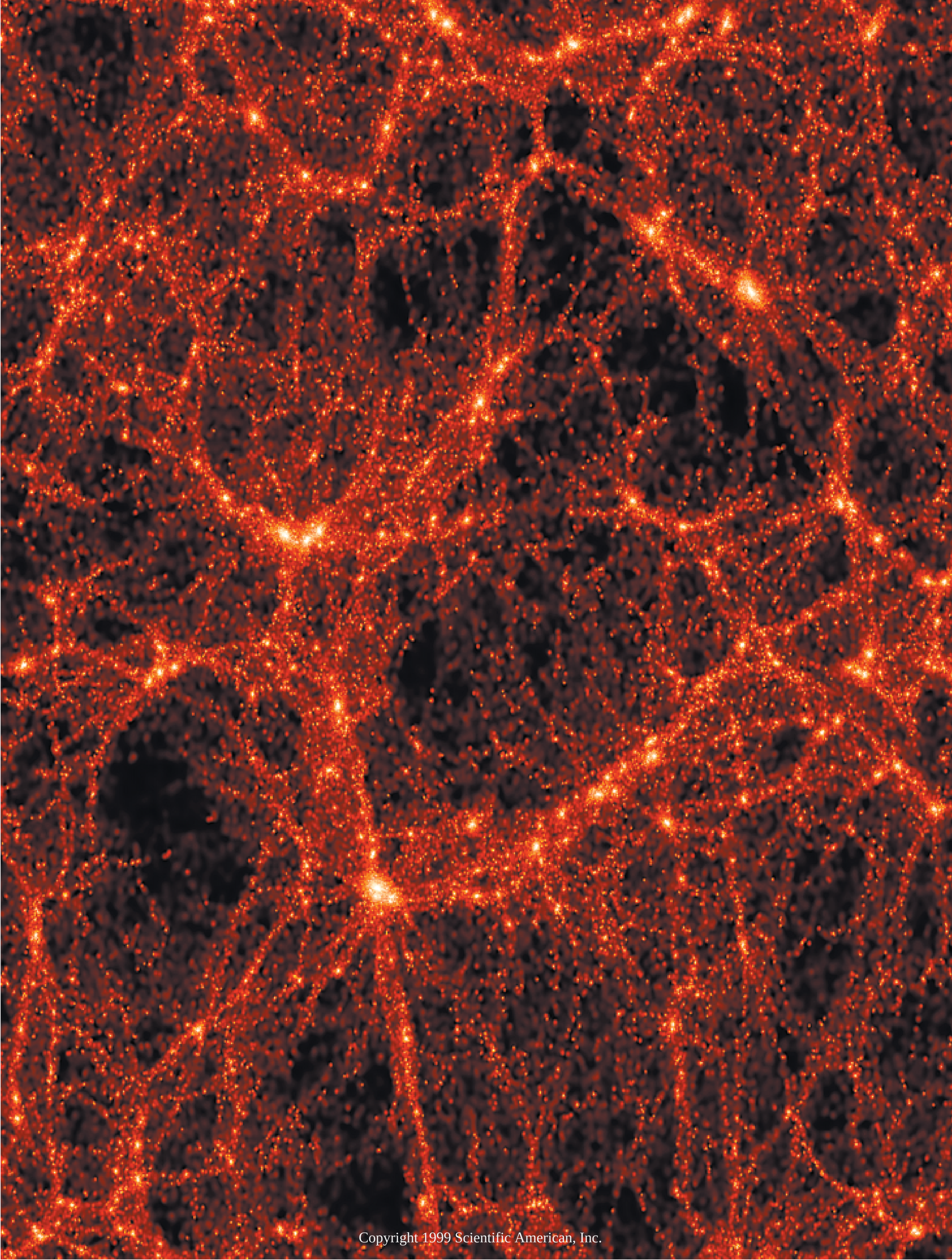
Cosmic exploration is preeminently a 20th-century achievement. Only in the 1920s did we realize that our Milky Way, with its 100 billion stars, is just one galaxy among millions. Our empirical knowledge of the universe has been accumulating ever since. We can now set our entire solar system in a grand evolutionary context, tracing its constituent atoms back to the initial instants of the big bang. If we were ever to discover alien intelligences, one thing we might share with them—perhaps the only thing—would be a common interest in the cosmos from which we have all emerged.

Using the current generation of ground-based and orbital observatories, astronomers can look back into the past and see plain evidence of the evolution of the universe. Marvelous images from the Hubble Space Telescope reveal galaxies as they were in remote times: balls of glowing, diffuse gas dotted with massive, fast-burning blue stars. These stars transmuted the pristine hydrogen from the big bang into heavier atoms, and when the stars died they seeded their galaxies with the basic building blocks of planets and life—carbon, oxygen, iron and so on. A Creator didn't have to turn 92 different knobs to make all the naturally occurring elements in the periodic table. Instead the galaxies act as immense ecosystems, forging elements and recycling gas through successive generations of stars. The human race itself is composed of stardust—or, less romantically, the nuclear waste from the fuel that makes stars shine.

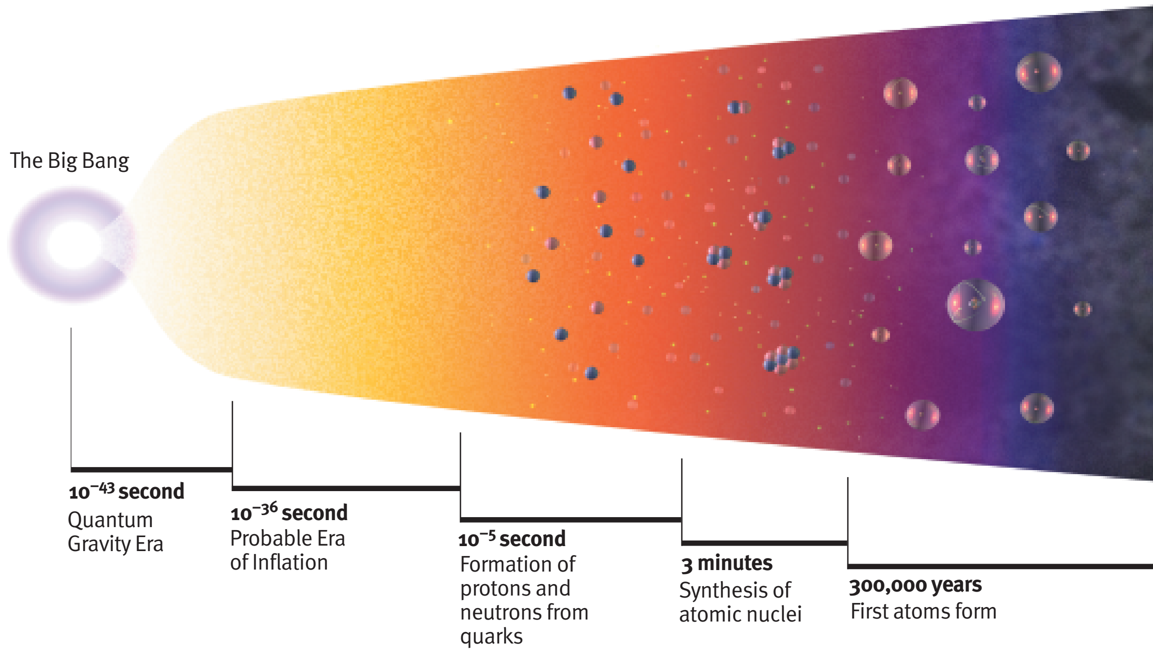
Astronomers have also learned much about the earlier, pregalactic era by studying the microwave background radiation that makes even intergalactic space slightly warm. This afterglow of creation tells us that the entire

Large-scale structure of the universe can be simulated by running cosmological models on a supercomputer. In this simulation, produced by the Virgo Consortium, each particle represents a galaxy.

VIRGO CONSORTIUM (J. M. COLBERG, H. M. P. COUCHMAN, G. EFSTATHIOU, C. S. FRENK, A. JENKINS, J. A. PEACOCK, F. R. PEARCE AND S. D. M. WHITE)

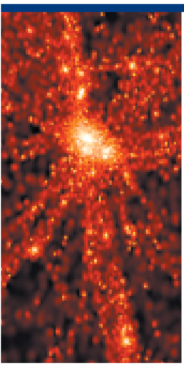


Cosmic timeline shows the evolution of our universe from the big bang to the present day. In the first instant of creation—the epoch of inflation—the universe expanded at a staggering rate. After about three minutes, the plasma of particles and radiation cooled enough to allow the formation of simple atomic nuclei; after another 300,000 years, atoms of hydrogen and helium began to form. The first stars and galaxies appeared about a billion years later. The ultimate fate of the universe—whether it will expand forever or recollapse—is still unknown, although current evidence favors perpetual expansion.



universe was once hotter than the centers of stars. Scientists can use laboratory data to calculate how much nuclear fusion would have happened during the first few minutes after the big bang. The predicted proportions of hydrogen, deuterium and helium accord well with what astronomers have observed, thereby corroborating the big bang theory.

At first sight, attempts to fathom the cosmos might seem presumptuous and premature, even in the closing days of the 20th century. Cosmologists have, nonetheless, made real progress in recent years. This is because what makes things baffling is their degree of complexity, not their sheer size—and a star is simpler than an insect. The fierce heat within stars, and in the early universe, guarantees that everything breaks down into its simplest constituents. It is the biologists, whose role it is to study the intricate multilayered structure of trees, butterflies and brains, who face the tougher challenge.



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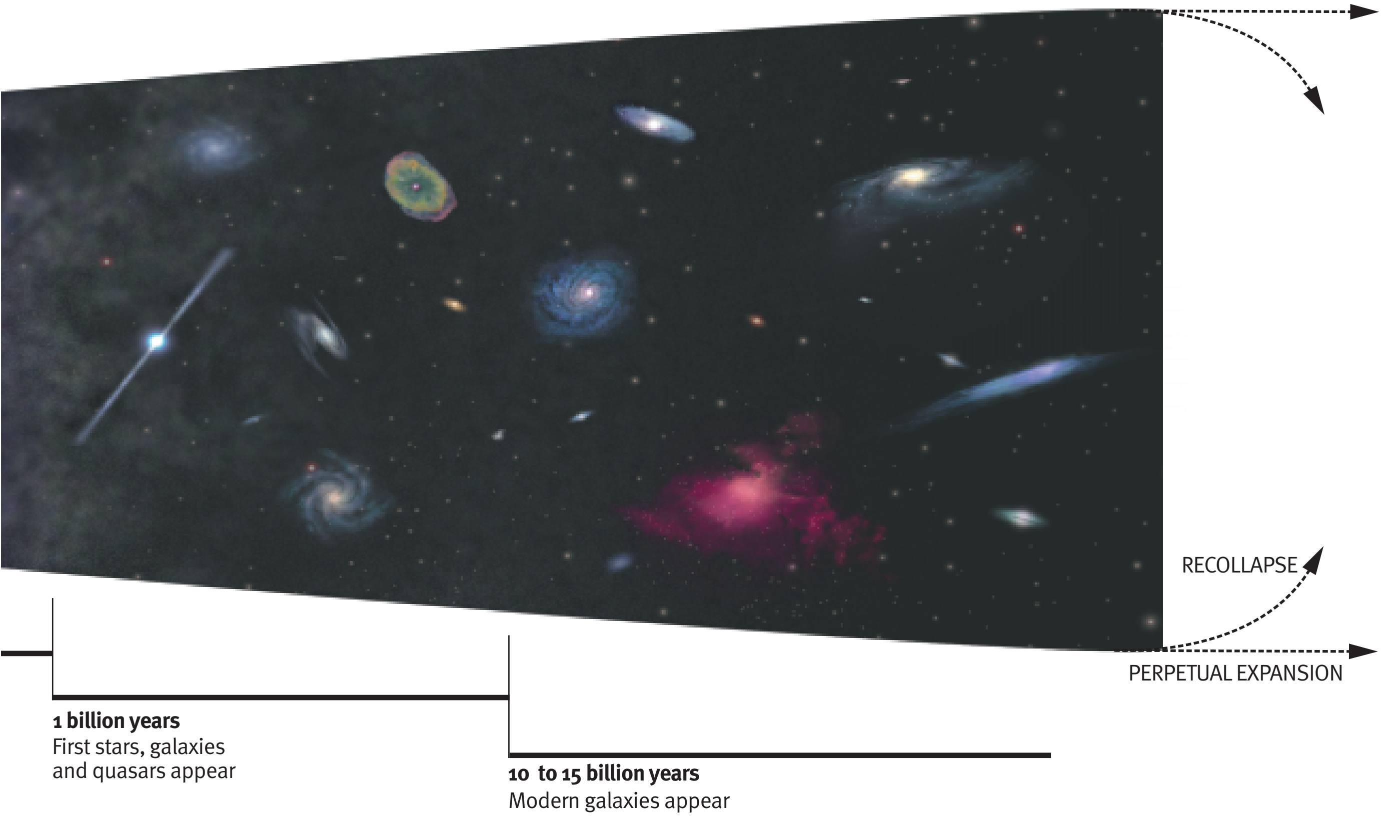
The progress in cosmology has brought new mysteries into sharper focus and raised questions that will challenge astronomers well into the next century. For example, why does our universe contain its observed mix of ingredients? And how, from its dense beginnings, did it heave itself up to such a vast size? The answers will take us beyond the physics with which we are familiar and will require new insights into the nature of space and time. To truly understand the history of the universe, scientists must discover the profound links between the cosmic realm of the very large and the quantum world of the very small.

It is embarrassing to admit, but astronomers still don't know what our universe is made of. The objects that emit radiation that we can observe—such as stars, quasars and galaxies—constitute only a small fraction of the universe's matter. The vast bulk of matter is dark and unaccounted for. Most cosmologists believe dark matter is composed of weakly interacting particles left over from the big bang, but it could be something even more exotic. Whatever the case, it is clear that galaxies, stars and planets are a mere afterthought in a cosmos dominated by quite different stuff. Searches for dark matter, mainly via sensitive underground experiments designed to detect elusive subatomic particles, will continue apace in the coming decade. The stakes are high: success would not only tell us what most of the universe is made of but would also probably reveal some fundamentally new kinds of particles.

Astronomers are also unsure how much dark matter there is. The ultimate fate of our universe—whether it continues expanding indefinitely or eventually changes course and collapses to the so-called big crunch—depends on the total amount of dark matter and the gravity it exerts. Current data indicate that the universe contains only about 30 percent of the matter that would be needed to halt the expansion. (In cosmologists' jargon, omega—the ratio of observed density to critical density—is 0.3.) The odds favoring perpetual growth have recently strengthened further: tantalizing observations of distant supernovae suggest that the expansion of the universe may be speeding up rather than slowing down. Some astronomers say the observations are evidence of an extra repulsive force that overwhelms gravity on cosmic scales—what Albert Einstein called the cosmological constant. The jury is still out on this



issue, but if the existence of the repulsive force is confirmed, physicists will learn something radically new about the energy latent in empty space.

Research is also likely to focus on the evolution of the universe's large-scale structure. If one had to answer the question "What's been happening since the big bang?" in just one sentence, the best response might be to take a deep breath and say, "Ever since the beginning, gravity has been amplifying inhomogeneities, building up structures and enhancing temperature contrasts—a prerequisite for the emergence of the complexity that lies around us now and of which we're a part." Astronomers are now learning more about this 10-billion-year process by creating "virtual universes" on their computers. In the coming years, they will be able to simulate the history of the universe with ever improving realism and then compare the results with what telescopes reveal.

Questions of structure have preoccupied astronomers since the time of Isaac Newton, who wondered why all the planets circled the sun in the same direction and in almost the same plane. In his 1704 work *Opticks* he wrote: "Blind fate could never make all the planets move one and the same way in orbits concentrick." Such a wonderful uniformity in the planetary system, Newton believed, must be the effect of divine providence.

Now astronomers know that the coplanarity of the planets is a natural outcome of the solar system's origin as a spinning disk of gas and dust. Indeed, we have extended the frontiers of our knowledge to far earlier times; cosmologists can roughly outline the history of the universe back to the very first second after the big bang. Conceptually, however, we're in little better shape than Newton was. Our understanding of the causal chain of events now stretches further back in time, but we still run into a barrier, just as surely as Newton did. The great mystery for cosmologists is the series of events that occurred less than one millisecond after the big bang, when the universe was extraordinarily small, hot and dense. The laws of physics with which we are familiar offer little firm guidance for explaining what happened during this critical period.

To unravel this mystery, cosmologists must first pin down—by improving and refining current observations—some of the characteristics of the universe when it was only one second old: its expansion rate, the size of its density fluctuations, and its proportions of ordinary atoms, dark matter and radiation. But to comprehend why our universe was set up this way, we must probe further back, to the very first tiny fraction of a microsecond. Such an effort will require theoretical advances. Physicists must discover a way to relate Einstein's theory of general relativity, which governs large-scale interactions in the cosmos, with the quantum principles that apply at very short distances [see "A Unified Physics by 2050?," by Steven Weinberg, on page 68]. A unified theory would be

Multiple universes are continually being born, according to some cosmologists. Each universe is shown here as an expanding bubble branching off from its "parent" universe. The changes in color represent shifts in the laws of physics from one universe to another.

ILLUSTRATIONS BY ALFRED T. KAMAJIAN

PAT RAWLINGS

Lunar observatories will greatly extend the reach of 21st-century astronomers. The far side of the moon is an ideal place for telescopes because of its absence of atmosphere and its utterly dark nights. (Sunlight reflected off Earth's surface cannot reach the far side, which never faces our planet.) Lunar ores can be used to build the instruments.

needed to explain what happened in the first crucial moments after the big bang, when the entire universe was squeezed into a space smaller than a single atom.

Astronomy is a subject in which observation is king. Now the same is true for cosmology—in contrast with the pre-1965 era, when speculation was largely unconstrained. The answers to many of cosmology's long-standing questions are most likely to come from the new telescopes now going into use. The two Keck Telescopes on Mauna Kea in Hawaii are far more sensitive than earlier observatories and thus can glimpse fainter objects. Still more impressive is the Very Large Telescope being built in northern Chile, which will be the world's premier optical facility when it is completed. Astronomers can take advantage of the Chandra X-ray Observatory, launched into orbit this past summer, and several new radio arrays on the ground. And a decade from now next-generation space telescopes will carry the enterprise far beyond what the Hubble can achieve.

Well before 2050 we are likely to see the construction of giant observatories in space or perhaps on the far side of the moon. The sensitivity and imaging power of these arrays will vastly surpass that of any instruments now in use. The new telescopes will target black holes and planets in other solar systems. They will also provide snapshots of every cosmological era going back to the very first light, when the earliest stars (or maybe quasars) condensed out of the expanding debris from the big bang. Some of these observatories may even be able to measure gravitational waves, allowing scientists to probe vibrations in the fabric of space-time itself.

The amount of data provided by all these instruments will be so colossal that the entire process of analysis and discovery will most likely be automated. Astronomers will focus their attention on heavily processed statistics for each population of objects they are studying and in this way find the best examples—for instance, the planets in other solar systems that are most like Earth. Researchers will also concentrate on extreme objects that may hold clues to physical processes that are not yet fully understood. One such object is the gamma-ray burster, which emits, for a few seconds, as much power as a billion galaxies. Increasingly, astronomers will use the heavens as a cosmic laboratory to probe phenomena that cannot be simulated on Earth.

Another benefit of automation will be open access to astronomical data that in the past were available only to a privileged few. Detailed maps of the sky will be available to anyone who can access or download them. Enthusiasts anywhere in the world will be able to check their own hunches, seek new patterns and discover unusual objects.

Intimations of a Multiverse?

Cosmologists view the universe as an intricate tapestry that has evolved from initial conditions that were imprinted in the first microsecond after the big bang. Complex structures and phenomena have unfolded from simple physical laws—we wouldn't be here if they hadn't. Simple laws, however, do not necessarily lead to complex consequences. Consider an analogue from the field of fractal mathematics: the Mandelbrot set, a pattern with an infinite depth of structure, is encoded by a short algorithm, but other simple algorithms that are superficially similar yield very boring patterns.

Our universe could not have become structured if it were not expanding at a special rate. If the big bang had produced fewer density fluctuations, the universe would have remained dark and featureless, with no galaxies or stars. And there are other prerequisites for complexity. If our universe had more than three spatial dimensions, planets could not stay in orbits around stars. If gravity were much stronger, it would crush living organisms of human size, and stars would be small and short-lived. If nuclear forces were a few percent weaker, only hydrogen would be stable: there would be no periodic table, no chemistry and no life. On the other hand, if nuclear forces were slightly stronger, hydrogen itself could not exist.

Some would argue that this fine-tuning of the universe, which seems so providential, is nothing to be surprised about, because we could not exist otherwise. There is, however, another interpretation: many universes may exist, but only some would allow creatures like us to emerge, and we obviously find ourselves in one of that subset. The seemingly designed features of our universe need then occasion no surprise.

Perhaps, then, our big bang wasn't the only one. This speculation dramatically enlarges our concept of reality. The entire history of our universe becomes just an episode, a single facet, of the infinite multiverse. Some universes might resemble ours, but most would be "stillborn." They would recollapse after a brief existence, or the laws governing them would not permit complex consequences.

Some cosmologists, especially Andrei Linde of Stanford University and Alex Vilenkin of Tufts University, have already shown how certain mathematical assumptions lead, at least in theory, to the creation of a multiverse. But such ideas will remain on the speculative fringe of cosmology until we really understand—rather than just guess at—the extreme physics that prevailed immediately after the big bang. Will the long-awaited unified theory uniquely determine the masses of particles and the strengths of the basic forces? Or are these properties in some sense accidental outcomes of how our universe cooled—secondary manifestations of still deeper laws governing an entire ensemble of universes?

This topic might seem arcane, but the status of multiverse ideas affects how we should place our bets in some ongoing cosmological controversies. Some theorists have a strong preference for the simplest picture of the cosmos, which would require an omega of 1—the universe would be just dense enough to halt its own expansion. They are unhappy with observations suggesting that the universe is not nearly so dense and with extra complications such as the cosmological constant. Perhaps we should draw a lesson from 17th-century astronomers Johannes Kepler and Galileo Galilei, who were upset to find that planetary orbits were elliptical. Circles, they thought, were simpler and more beautiful. But Newton later explained all orbits in terms of a simple, universal law of gravity. Had Galileo still been alive, he would have surely been joyfully reconciled to ellipses.

The parallel is obvious. If a low-density universe with a cosmological constant seems ugly, maybe this shows our limited vision. Just as Earth follows one of the few Keplerian orbits around the sun that allow it to be habitable, our universe may be one of the few habitable members of a grander ensemble.

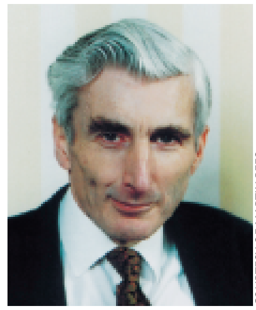
A Challenge for the New Millennium

As the 21st century dawns, scientists are expanding humanity's store of knowledge on three great frontiers: the very big, the very small and the very complex. Cosmology involves them all. In the coming years, researchers will focus their efforts on pinning down the basic universal constants, such as omega, and on discovering what dark matter is. I think there is a good chance of achieving both goals within 10 years. Maybe everything will fit the standard theoretical framework, and we will successfully determine not only the relative abundance of ordinary atoms and dark matter in the universe but also the cosmological constant and the primordial density fluctuations. If that happens, we will have taken the measure of our universe just as, over the past few centuries, we have learned the size and shape of Earth and our sun. On the other hand, our universe may turn out to be too complicated to fit into the standard framework. Some may describe the first outcome as optimistic; others may prefer to inhabit a more complicated and challenging universe!

In addition, theorists must elucidate the exotic physics of the very earliest moments of the universe. If they succeed, we will learn whether there are many universes and which features of our universe are mere contingencies rather than the necessary outcomes of the deepest laws. Our understanding will still have limits, however. Physicists may someday discover a unified theory that governs all of physical reality, but they will never be able to tell us what breathes fire into their equations and what actualizes them in a real cosmos.

Cosmology is not only a fundamental science; it is also the grandest of the environmental sciences. How did a hot amorphous fireball evolve, over 10 to 15 billion years, into our complex cosmos of galaxies, stars and planets? How did atoms assemble—here on Earth and perhaps on other worlds—into living beings intricate enough to ponder their own origins? These questions are a challenge for the new millennium. Answering them may well be an unending quest. SA

The Author



COURTESY OF MARTIN REES

MARTIN REES is Royal Society Research Professor at the University of Cambridge and holds the honorary title of Astronomer Royal. He was previously director of the Cambridge Institute of Astronomy and before that a professor at the University of Sussex. His research interests include black holes, galaxy formation and high-energy astrophysics. He also lectures and writes extensively for general audiences. His recent books are *Gravity's Fatal Attraction* (Scientific American Library, 1996, with Mitchell C. Begelman), *Before the Beginning* (Perseus Books, 1998) and *Just Six Numbers* (Basic Books, in press).

Further Information

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