

# Exploring

IN THIS CENTURY COSMOLOGISTS WILL UNRAVEL  
THE MYSTERY OF OUR UNIVERSE'S BIRTH—

# Our Universe

AND PERHAPS PROVE THE EXISTENCE OF OTHER  
UNIVERSES AS WELL

# and Others

BY MARTIN REES

## 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

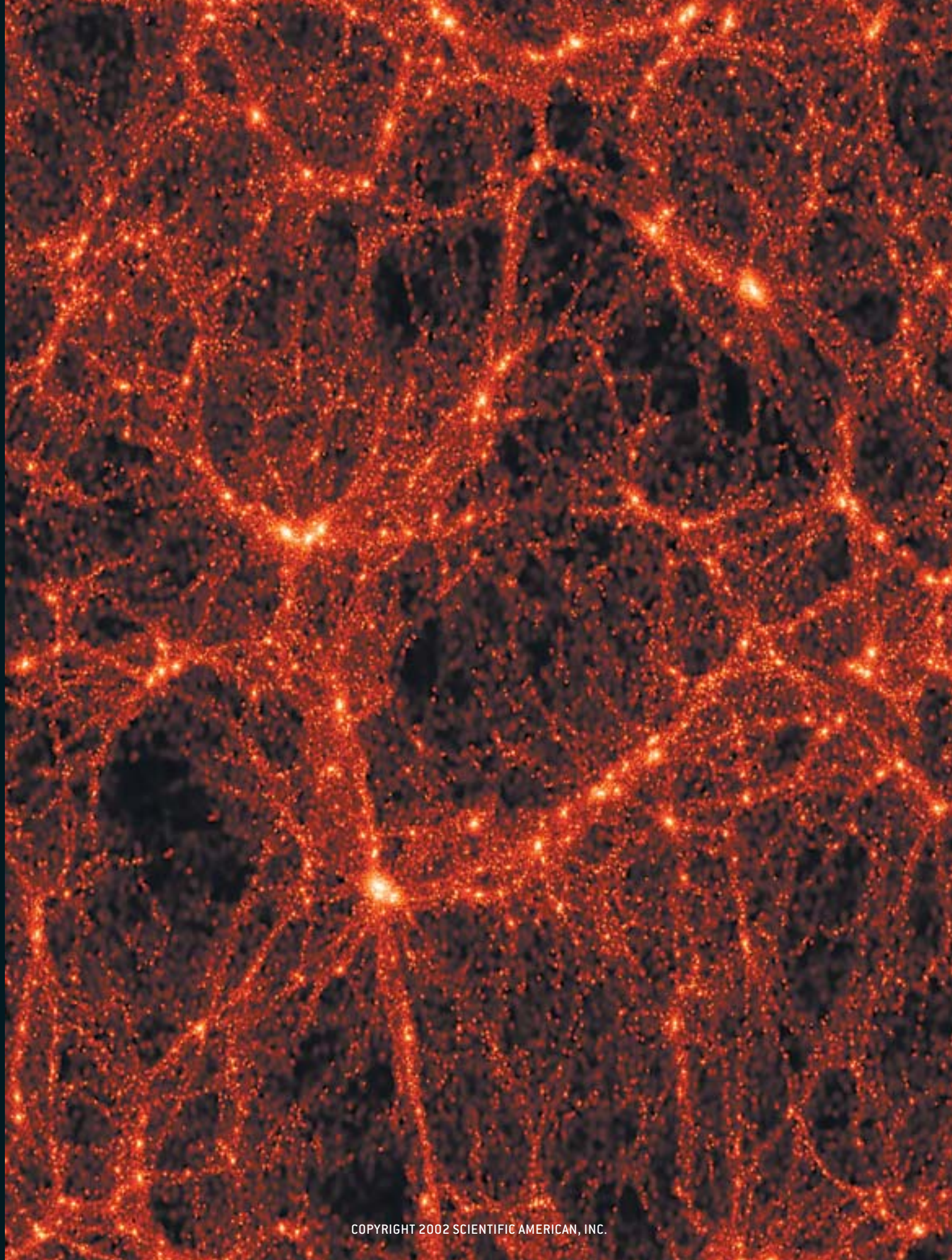
all the naturally occurring elements in the periodic table. Instead the galaxies act as immense ecosystems, forging elements and recycling gas through successive generations of stars. The human race itself is composed of stardust—or, less romantically, the nuclear waste from the fuel that makes stars 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 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

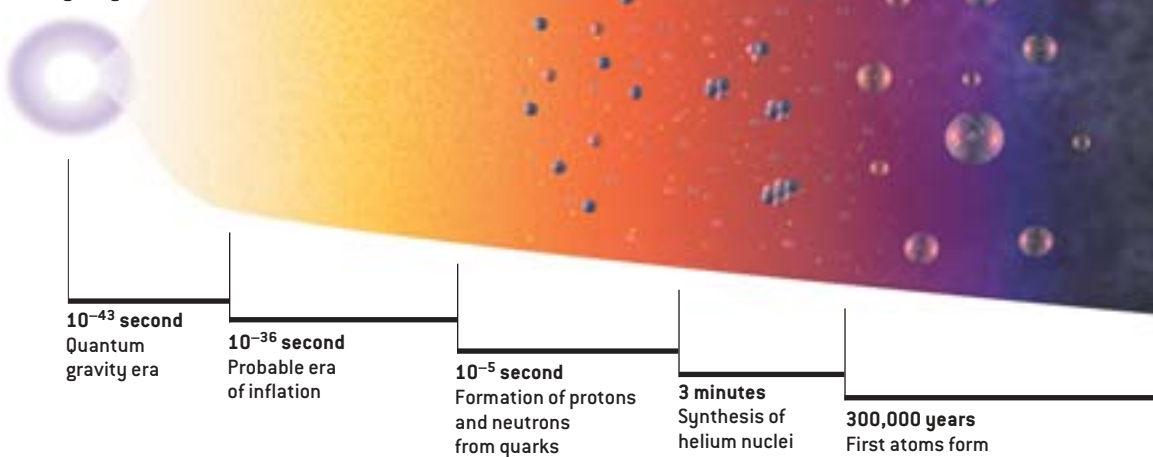
LARGE-SCALE STRUCTURE of the universe can be simulated by running cosmological models on a supercomputer. In this simulation, produced by the Virgo Consortium, each particle represents a galaxy.

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 TIME LINE** 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.

The big bang



presumptuous and premature, even at the start of the 21st century. Cosmologists have, nonetheless, made remarkable 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.

The progress in cosmology has brought new mysteries into sharper focus and raised questions that will challenge astronomers well into this 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

derground experiments designed to detect elusive subatomic particles, will continue apace in this 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.

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

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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 un-

derground experiments designed to detect elusive subatomic particles, will continue apace in this 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.

that the expansion of the universe may be speeding up rather than slowing down. These observations may indicate that an extra force overwhelms gravity on cosmic scales—a phenomenon perhaps related to what Albert Einstein called the cosmological constant, a form of energy latent in empty space itself that (unlike ordinary matter) has negative pressure and causes a repulsion. Studies of small nonuniformities in the background radiation reveal that our universe is “flat”—in the sense that the angles of a large triangle drawn in space add up to 180 degrees. Taken in conjunction with one another, these lines of evidence suggest that 5 percent of our universe (or slightly less) is composed of ordinary atoms, about 25 percent is dark matter and the other 70 percent is the even more perplexing dark energy.

Research is also likely to focus on the evolution of the universe's large-scale structure. If one had to answer the question



**1 billion years**  
First stars, galaxies and quasars appear

**10 billion to 15 billion years**  
Modern galaxies appear

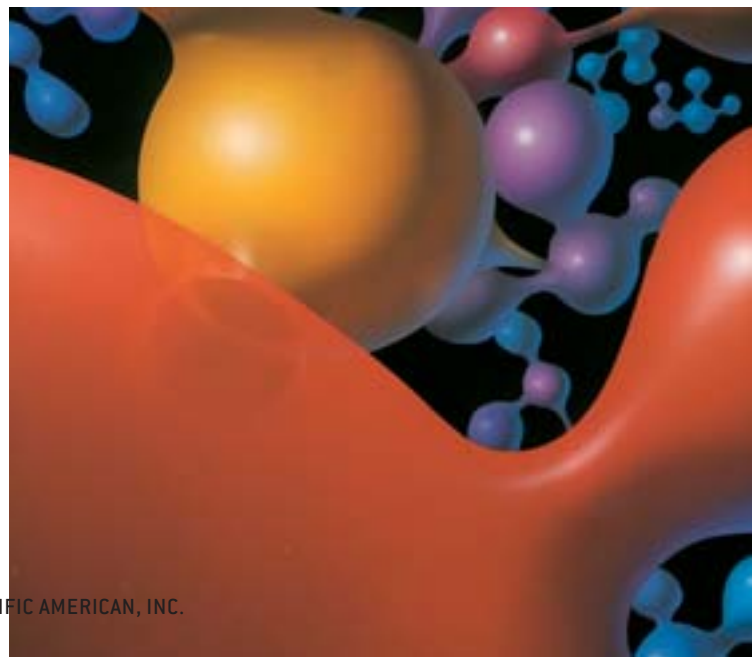
“What’s been happening since the big bang?” in just one sentence, the best response might be to take a deep breath and say, “Ever since the beginning, gravity has been amplifying inhomogeneities, building up structures and enhancing temperature contrasts—a prerequisite for the emergence of the complexity 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 concentric.” 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 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 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, to the quantum principles that apply at very short distances. A unified

**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.





**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, free of reflected sun and radio transmissions from Earth. Lunar ores can be used to build the instruments.

theory would be 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 telescopes that have recently gone 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 European Southern Observatory's Very Large Telescope at Paranal in northern Chile—a linked array of four telescopes, each with mirrors eight meters in diameter. In space, astronomers can take advantage of the Chandra X-ray Observatory and its European counterpart, XMM-Newton. Several new instruments are under construction to detect radio waves, infrared emissions and cosmic rays. And a decade from now next-generation space telescopes will carry the enterprise far beyond what the Hubble can achieve.

Well before 2050 we will probably 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 spacetime 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 to only 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

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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, 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.

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, an-

plained all orbits in terms of a simple, universal law of gravity. Had Galileo still been alive, he surely would have 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.

## The Next Challenges

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 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

Perhaps our **big bang wasn't the only one;**  
many universes may exist in **the infinite multiverse.**

other interpretation: many universes may exist, but only some would allow creatures like us to emerge.

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 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 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 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 and dark energy. 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 ex-

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### MORE TO EXPLORE

**Planet Quest: The Epic Discovery of Alien Solar Systems.** Ken Croswell. Free Press, 1997.

**The Little Book of the Big Bang: A Cosmic Primer.** Craig J. Hogan. Copernicus, 1998.