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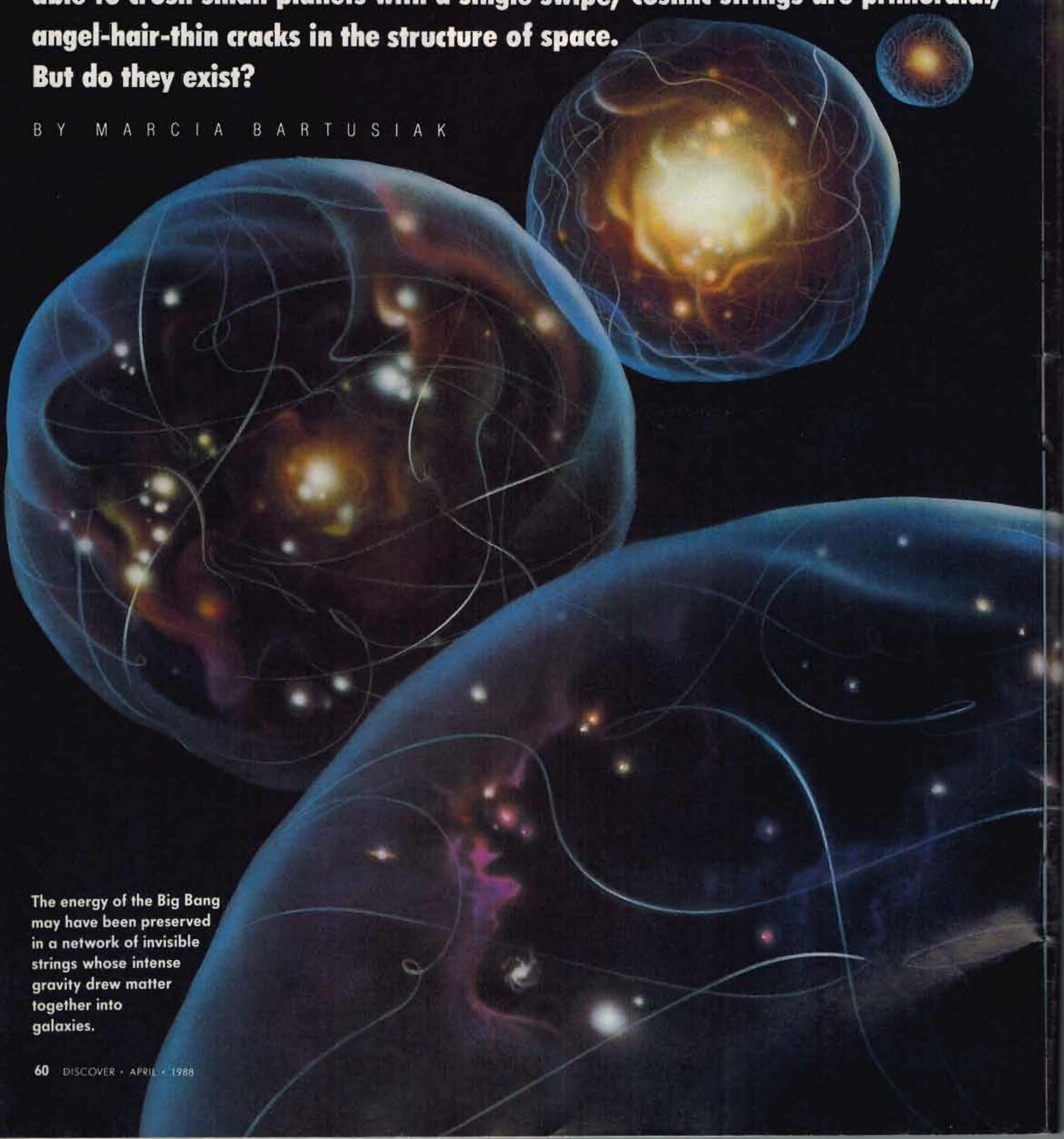
COSMIC STRINGS

Faster (by far) than a speeding bullet, more powerful than a supernova, able to crush small planets with a single swipe, cosmic strings are primordial, angel-hair-thin cracks in the structure of space. But do they exist?

BY MARCIA BARTUSIAK



The energy of the Big Bang may have been preserved in a network of invisible strings whose intense gravity drew matter together into galaxies.

DANGER: MEN WORKING ABOVE was the warning. The maintenance sign was temporarily erected in the towering lobby of the Fermi National Accelerator Laboratory, where 15 tiers of glass-walled offices rise up like a modern-day Gothic cathedral. The irony in the message amused the physicists, men and women alike, entering Fermilab's headquarters; many of them have a professional interest in recreating the hellish environment of the Big Bang.

Unfortunately that goal can't be fully attained in laboratories on Earth—not even at Fermilab, which currently boasts the world's most powerful atom smasher. But the Big Bang is not beyond the imagination of theorists. And if their latest musings are correct, relics of that first all-creating explosion may be preserved in space today.

The universe, in this view, may have been built on a scaffolding of string. Not ordinary string, of course, but cosmic string: invisible threads that are thinner than an atom, horrifically energetic—because the energy of the Big Bang is inside them—and disconcertingly eccentric in their behavior. The strands would be sparsely spread, like an unraveled skein of yarn, across the length and breadth of the cosmos and would move at near light speed.

Not since the 1960s, when the notion of stars collapsing into black holes was the theoretical rage, has an alleged astronomical object raised so many eyebrows. ("Black holes are mild by comparison," quips Neil Turok of Fermilab.) As little as five years ago most researchers considered cosmic string to be just another theoretical flight of fancy. But then this wildest of ideas started answering questions that no other cosmological theory could handle. "That made us think, 'Maybe there's something to this,' " says University of Chicago astrophysicist David Schramm.

In particular, cosmic strings may offer a solution to one of cosmology's most nagging problems: How did billions of galaxies, each incorporating billions of stars, emerge from the smooth, primeval plasma spewed forth by the Big Bang? Whether string theory represents a momentous breakthrough on this fundamental question or merely wishful thinking remains to be seen. But one of the virtues of the theory—unusual in the measurement-starved science of cosmology—is that it can in principle be tested by observation. Although the strings themselves are invisible, their effects should not be. "Nature," says Edward "Rocky" Kolb, head of Fermilab's astrophysics group, "will be the ultimate critic."

The idea of cosmic string originated in particle physics

ILLUSTRATION BY BOB WOOD/SRW INC.

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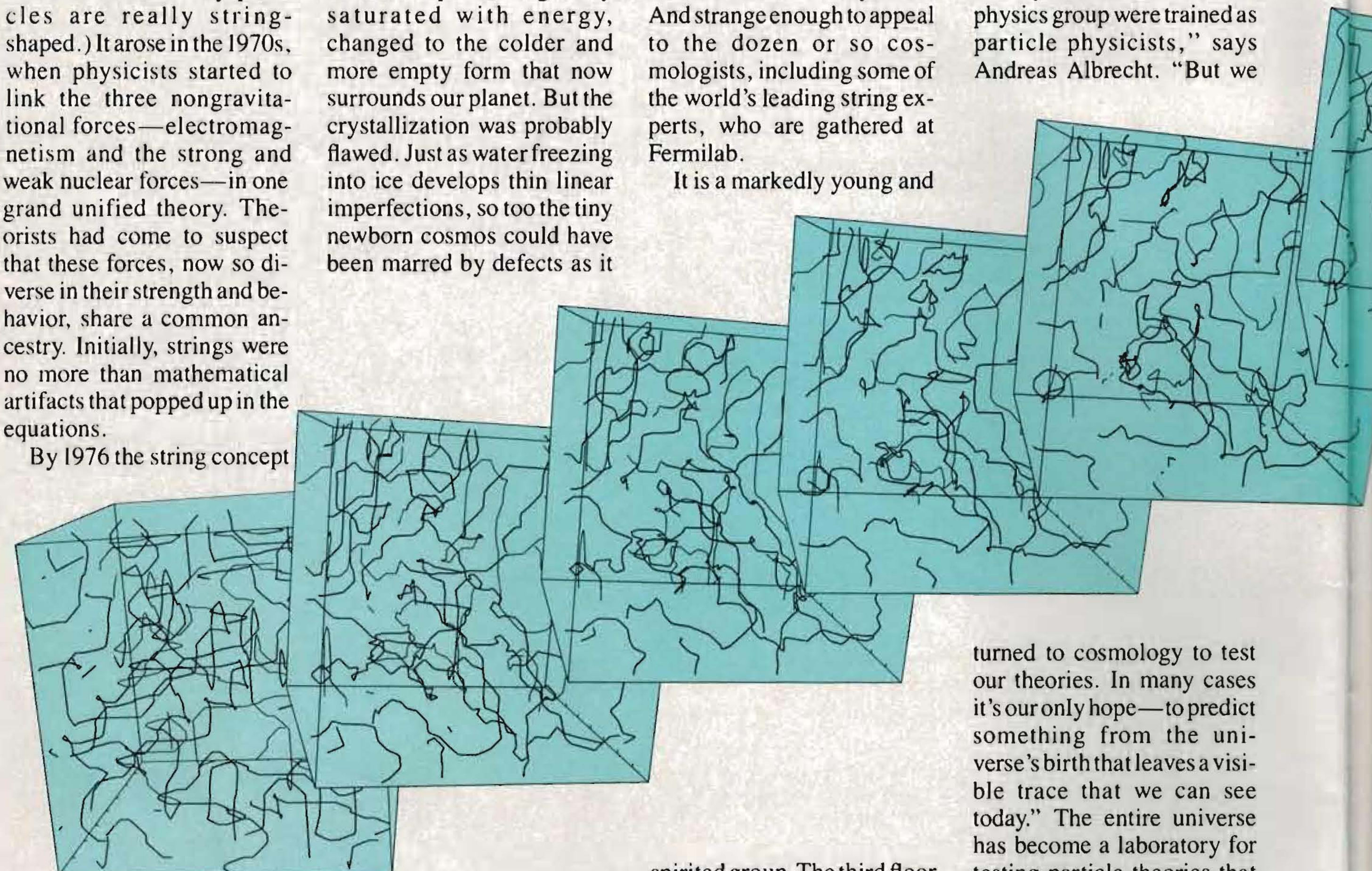
rather than in cosmology. (Despite the name, cosmic string has nothing to do with superstring theory, which holds that elementary particles are really string-shaped.) It arose in the 1970s, when physicists started to link the three nongravitational forces—electromagnetism and the strong and weak nuclear forces—in one grand unified theory. Theorists had come to suspect that these forces, now so diverse in their strength and behavior, share a common ancestry. Initially, strings were no more than mathematical artifacts that popped up in the equations.

By 1976 the string concept had become a bit more tangible, thanks to Tom Kibble of the Imperial College in London. Kibble was considering the cosmological consequences of grand unified theories. He was particularly interested in the conditions 10^{-35} second after the Big Bang, when temperatures in the embryonic cosmos were dropping below 1,000 trillion trillion degrees. That was the moment when grand unification came to an end; when forces and particles, formerly indistinguishable, assumed their separate identities.

Cosmologists like to visualize this momentous transition as a sort of "crystallization": space, originally saturated with energy, changed to the colder and more empty form that now surrounds our planet. But the crystallization was probably flawed. Just as water freezing into ice develops thin linear imperfections, so too the tiny newborn cosmos could have been marred by defects as it rapidly cooled and ballooned outward.



The cosmic defects, Kibble figured, would be slender strands of highly concentrated mass-energy—actual remnants of the original fireball—that endure to this day, weaving a vast network of cracks in the texture of space-time. Inside each string the searing conditions of grand unification would still reign: particles such as quarks and electrons would look alike; the weak nuclear force would be as powerful as the strong.

Kibble's vision was a strange one indeed—strange enough to make physicists wonder whether such bizarre entities could actually exist. And strange enough to appeal to the dozen or so cosmologists, including some of the world's leading string experts, who are gathered at Fermilab.

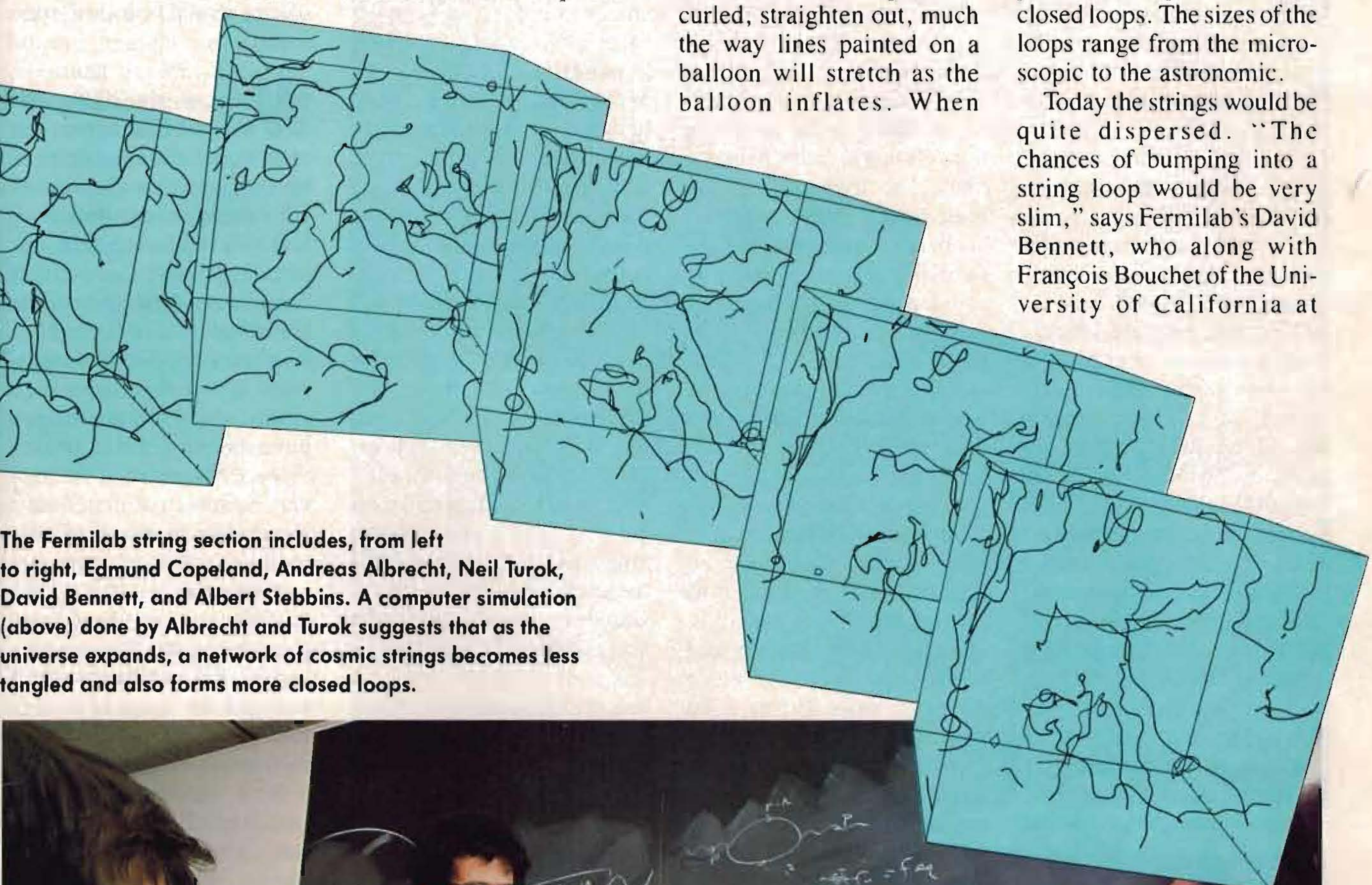
It is a markedly young and spirited group. The third floor of Fermilab, where these lunchtime volleyball players hang out when they are working, is a place where blackboards are filled not only with elaborate mathematical exotica but also with lighthearted cartoons; where a homemade poster announces the sale of used protons; and where novel ideas are greeted with childlike enthusiasm. The prevailing sense of fun seems altogether appropriate for proponents of string theory, which has been called particle physics' most entertaining contribution to cosmology.

The Fermilab workers themselves, cosmologists at a particle accelerator facility, symbolize the marriage of these two disciplines—the "inner space–outer space" connection, as they call it. "Many of us here in the astrophysics group were trained as particle physicists," says Andreas Albrecht. "But we turned to cosmology to test our theories. In many cases it's our only hope—to predict something from the universe's birth that leaves a visible trace that we can see today." The entire universe has become a laboratory for testing particle theories that are beyond the reach of terrestrial experiments.

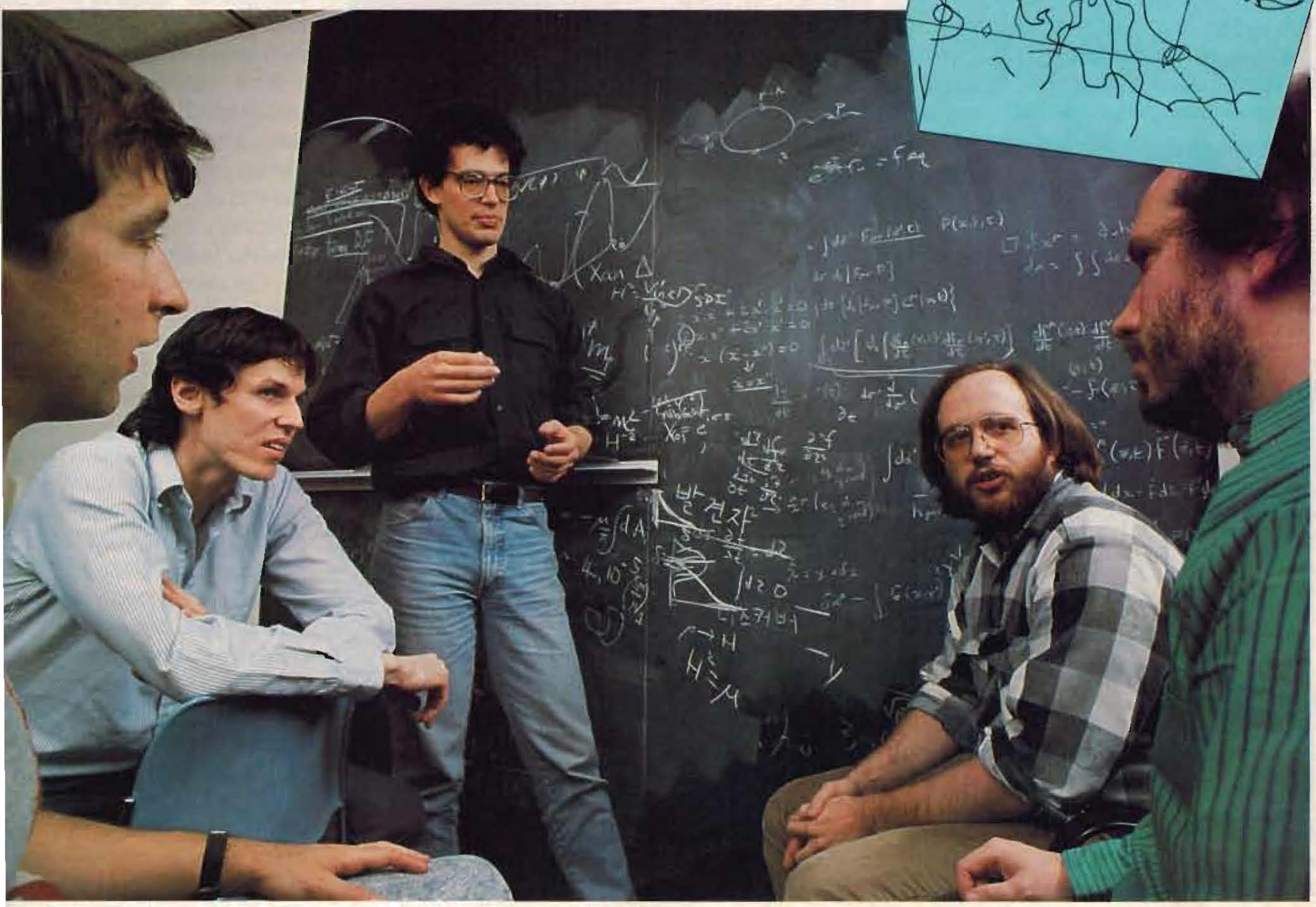
The tools of the Fermilab group are computers rather than particle accelerators or telescopes. Albrecht and Turok, a British protégé of Kibble's who recently joined Fermilab, have done computer simulations that show how cosmic strings might develop over time. "Through these simulations we gain an intuition that we can take to the equations," says Albrecht. "String evolution is a very visual process."

At birth the strings emerge in the computer pictures as a tousled mesh looking not unlike a Jackson Pollock painting. Some of the strands are essentially infinite in length, extending clear across the visible universe; others form closed loops. As space expands, carried outward by the momentum of the primordial explosion, the string network also evolves. The long strands, at first tangled and curled, straighten out, much the way lines painted on a balloon will stretch as the balloon inflates. When strings curl back upon themselves, the curls can simply pinch off to produce more closed loops. The sizes of the loops range from the microscopic to the astronomic.

Today the strings would be quite dispersed. "The chances of bumping into a string loop would be very slim," says Fermilab's David Bennett, who along with François Bouchet of the University of California at



The Fermilab string section includes, from left to right, Edmund Copeland, Andreas Albrecht, Neil Turok, David Bennett, and Albert Stebbins. A computer simulation (above) done by Albrecht and Turok suggests that as the universe expands, a network of cosmic strings becomes less tangled and also forms more closed loops.



If an atom were the size of our solar system, a cosmic string would still be thinner than a virus.

Berkeley has simulated string evolution on a Cray-2 supercomputer. According to Bennett, the average loop would now be about a million light-years in circumference; the nearest one might be as much as a billion light-years from Earth, far beyond the Milky Way and its neighboring galaxies. Long strings would be even rarer, perhaps only four or five meandering across the universe.

Besides being the longest and possibly the oldest structure in the known universe, a cosmic string would be the thinnest as well; its diameter would be 100,000,000,000,000,000 times smaller than a proton. If a single atom and a cosmic string were both enlarged until the atom was the size of our solar system, the string would still be much thinner than a virus. Yet each inch of this stringy stuff would be as massive as the entire Swiss Alps. "Just several miles of string would outweigh the Earth," notes Albrecht.

And every string would be terribly restless, rushing through space at a velocity nearly equal to the speed of light (186,000 miles per second). The loops would vibrate madly like crazed rubber bands. In the process they would emit a continual stream of gravitational waves: ripples in the very fabric of space-time. As a loop radiated away this energy, it would gradually shrink and disappear. The smaller the loop, the quicker its disappearing act; a loop 1,000 light-years in circumference, for example, would die in about 10 million to 100 million years. "But the long strings, which are permanent, just chop off more loops," says Turok, "to maintain a steady supply."

What would happen if a cosmic string were to run into a planet? Being so thin, a string could actually whiz through a planet without bumping into a single atomic nucleus. But its intense gravitational field would wreak havoc nonetheless. If a string were to slice through Earth at the equator, for instance, the North and South poles would rush toward each other at 10,000 miles per hour.

Albrecht and Turok are not eager to discuss the destructive power of cosmic strings. ("High-energy physicists are too often identified with explosions and detonations," they explain.) They and their colleagues are more comfortable pondering a string's aesthetic qualities. What kind of sound would a string make if you could pluck it? the physicists gleefully ask during a lunchtime discussion. With a swift calculation, Turok determines that a piece of string, suitably cut to fit a violin, would produce a resounding tone about 20 octaves above middle C. The music of the spheres, it seems, would be a shrill tune indeed.

When, in the 1930s, Sir Arthur Eddington, the most noted astrophysicist of his day, was first confronted with the startling notion of bottomless black holes, objects so massive that no light can escape their gravity, he remarked that there ought to be a law of nature to prevent stars from behaving in such absurd ways. Cosmic strings have faced similar prejudices. "No one took the idea very seriously at first," says Turok; like so much of cosmology, it seemed too vague and speculative. But by the mid-1980s a wondrous new picture of the universe's large-scale structure had changed the status of strings and provided them with a raison d'être.

New observations have shattered the old doctrine that the universe is homogeneous, with galaxies and clusters of galaxies scattered uniformly through space like a mist. Today's astronomers are discovering that galaxies are distributed in a curious pattern: they seem to sit on the surface of huge, nested bubbles. Inside the bubbles are enormous voids, as much as 250 million light-years across, where few if any galaxies are found. The universe may best be described not as a mist but as a foam, like the ample head on a newly poured glass of beer.

Many cosmologists think there has not been enough time for gravity alone to push galaxies into these special positions. They suspect that the bubbly structures are an imprint—a relic—of processes that occurred at the earliest moments of creation.

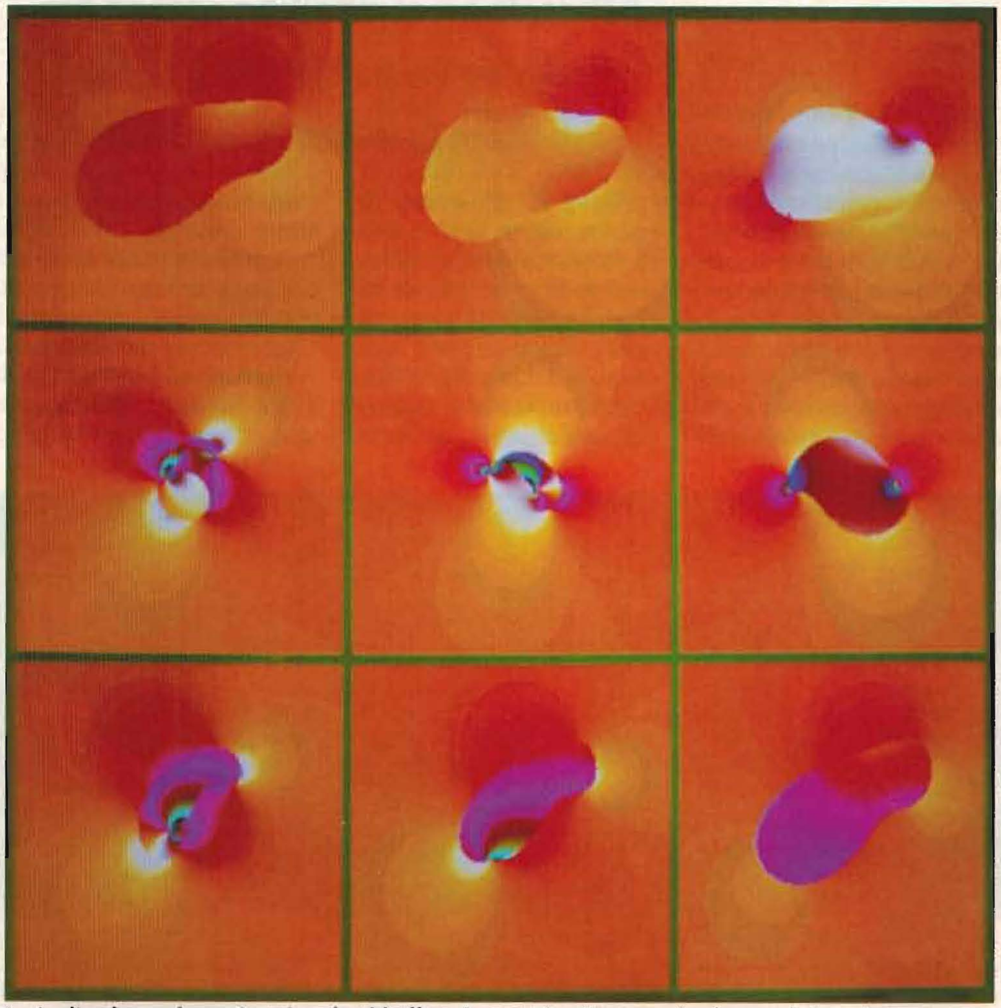
Galaxies (white dots) seem to sit on the surface of bubbles that surround huge voids. This map, made by Harvard researchers, shows a three-dimensional wedge of space stretching several hundred million light-years to the north of our Milky Way, which is at the bottom.

IMAGE COURTESY VALERIE DE LAPPARENT, MARGARET GELLER, AND JOHN HUCHRA, HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS

But what processes? Cosmologists are nowhere near agreement on an answer to that question. They do know, however, that the correct theory must explain not only why galaxies seem to be distributed in bubbles, but also why galaxies exist at all. How did the universe, which must have been extremely smooth and uniform in the first days after the Big Bang, ultimately become so lumpy?

Several answers have been proposed, but lately an idea involving cosmic strings has been attracting much attention. A leading exponent of the idea has been Alexander Vilenkin of Tufts University. (Vilenkin, who also works on the creation of universes from nothing, has no problem dealing with the bizarreness of string; "I have this habit of working on outlandish things," he admits.) In the early 1980s Vilenkin suggested that loops of cosmic string, because of their powerful gravitational fields, could have served as the seeds of galaxies and galaxy clusters.

The scenario goes like this: When the universe was young, relatively small string loops, about 100 light-years in circumference, attracted vast assemblages of matter around themselves. Slowly shrinking as they oscillated and released gravitational energy, the loops eventually vanished, leaving behind an array of galaxies as their calling cards. Before disappearing, though, the small loops flocked around larger loops; thus clusters of galaxies were born. At the same time, even larger loops (or long, unlooped strings) raced through the primeval gases and stirred up wide, sheetlike wakes; the wakes eventually turned into superclusters, or clusters of clusters.



A wiggling loop of cosmic string should affect the cosmic microwave background: the microwaves should be hotter (orange and purple) behind the string and cooler (yellow) in front of it.

Interest in this scheme soared in 1985, when Turok linked theory with observation. He pointed out that Abell clusters, the richest galaxy groups of their kind, tend to be distributed in space in the same way that large string loops are distributed in his numerical simulations. Moreover, the dense association of galaxies in an Abell cluster accurately mimics the way small loops gather around a large one. Turok's success was one of the first indications that a network of cosmic strings might be just what is needed to explain the universe's diverse structures. What was once a madcap theoretical fantasy began to look increasingly plausible.

String theorists have found another possible link with the real world, in the form of an elaborate calculation. The gravitational pull of a string loop depends on its mass and therefore on its density. By looking at the sky and asking, "How dense must cosmic string be to produce the galaxies and clusters I see?" theorists arrived at a certain number: around 10^{21} grams (1,000 trillion tons) per centimeter—which is just the density of string that is expected to arise when a grand unified force fragments into its separate components. The match between the two calculations could be sheer coincidence. Or it could be a telling clue that string devotees are on the right track.

One problem with Vilenkin's scenario is that it doesn't explain adequately how cosmic strings could form the giant bubbles and voids. But an added characteristic might do the trick. Upon analyzing an obscure detail in the mathematical equations describing string, Edward Witten of the Institute for Advanced Study in Princeton realized that cosmic string could be superconducting; that is, it could conduct an electric current with no resistance. (The current would be carried by pointlike unification particles.) A newborn string, racing through a primordial magnetic field, would then start an immense current, perhaps as much as a hundred million trillion amperes, endlessly flowing within it.

Witten, along with Jeremiah Ostriker and

"There's no compelling reason for strings to exist. Choosing to deal with them is a matter of taste."

Christopher Thompson of Princeton University, saw that superconducting strings would have dramatic effects. Flopping around furiously, the strings would emit floods of electromagnetic radiation, much the way a current running up and down an antenna emits radio waves. In the early universe this intense radiation would have pushed on the primeval gases—and could conceivably have scoured out the huge voids now seen in the distribution of galaxies.

Of course, such speculations can be carried too far, just as black holes were once blamed for every quirk in the heavens. "Strings don't have to be superconducting," stresses Witten. "It is merely a possibility." Ostriker, though, once drolly noted that if superconducting strings are not responsible for the large-scale structure of the universe, "it is likely to be something as bad—or worse."

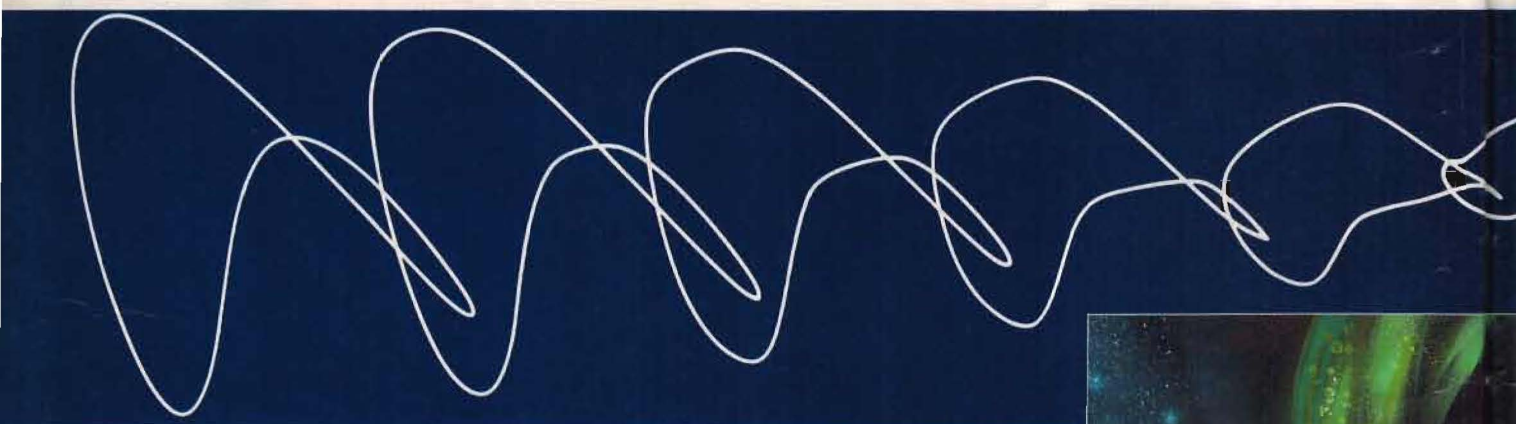
"Strings are so unusual," says Vilenkin, "that we're always trying to connect them to phenomena equally as unusual." For example, Vilenkin and George Field of the Harvard-Smithsonian Center for Astrophysics have suggested that superconducting string loops, vigorously oscillating in the hearts of quasars, might be responsible for the fountains of energy seen jetting out of those bright young galaxies. A similar origin has also been proposed for gamma-ray bursts, mysterious events that sporadically pop off in the sky. "Most of these models will probably turn out to be wrong," admits Vilenkin. But that isn't deterring the speculation.

Indeed, cosmic strings seem to be replacing black holes as the theoretical darling of astrophysics. But whereas black holes are virtually inevitable—given the well-tested laws of general relativity—strings are appreciably more iffy. "At the moment, there's no compelling theoretical reason for strings to exist," says University of Arizona astrophysicist Simon White, a veteran at simulating the large-scale structure of the universe. "In some ways, choosing to deal with them is a matter of taste." Even the most ardent string advocates agree with White, and they continually stress that all their ideas remain highly speculative. Certainty will come only when astronomers pinpoint a string in the sky.

Astronomers are usually not eager to hunt for hypothetical objects; telescope time is simply too precious. Nevertheless, a few cosmic-string searches are under way. "There's been so much theoretical work on these objects," explains Craig Hogan of the University of Arizona, "that it would be foolish not to follow it up. Strings, if they exist, would tell us about high-energy processes that are otherwise inaccessible to us."

Though invisible to the eye, a string might be unmasked by its dramatic gravitational effects. Vilenkin first pointed this out. If a string were situated between Earth and a faraway galaxy, it would split the flow of light from the galaxy the way a rock splits a stream of water. The result: We'd see two images of the galaxy instead of just one. This effect is known as gravitational lensing. A number of double quasars have been sighted, but cosmic string is not necessarily the cause; other celestial obstacles, such as massive clusters of galaxies, can also act as gravitational lenses. Hence the need for additional tests.

Hogan has programmed a computer to scan hundreds of electronic images, made with a telescope on Kitt Peak, near Tucson, for signs of cosmic string. He's on the lookout for a particular pattern. "A chain of galaxy pairs across the sky would be a strong signature of a string," he explains. A

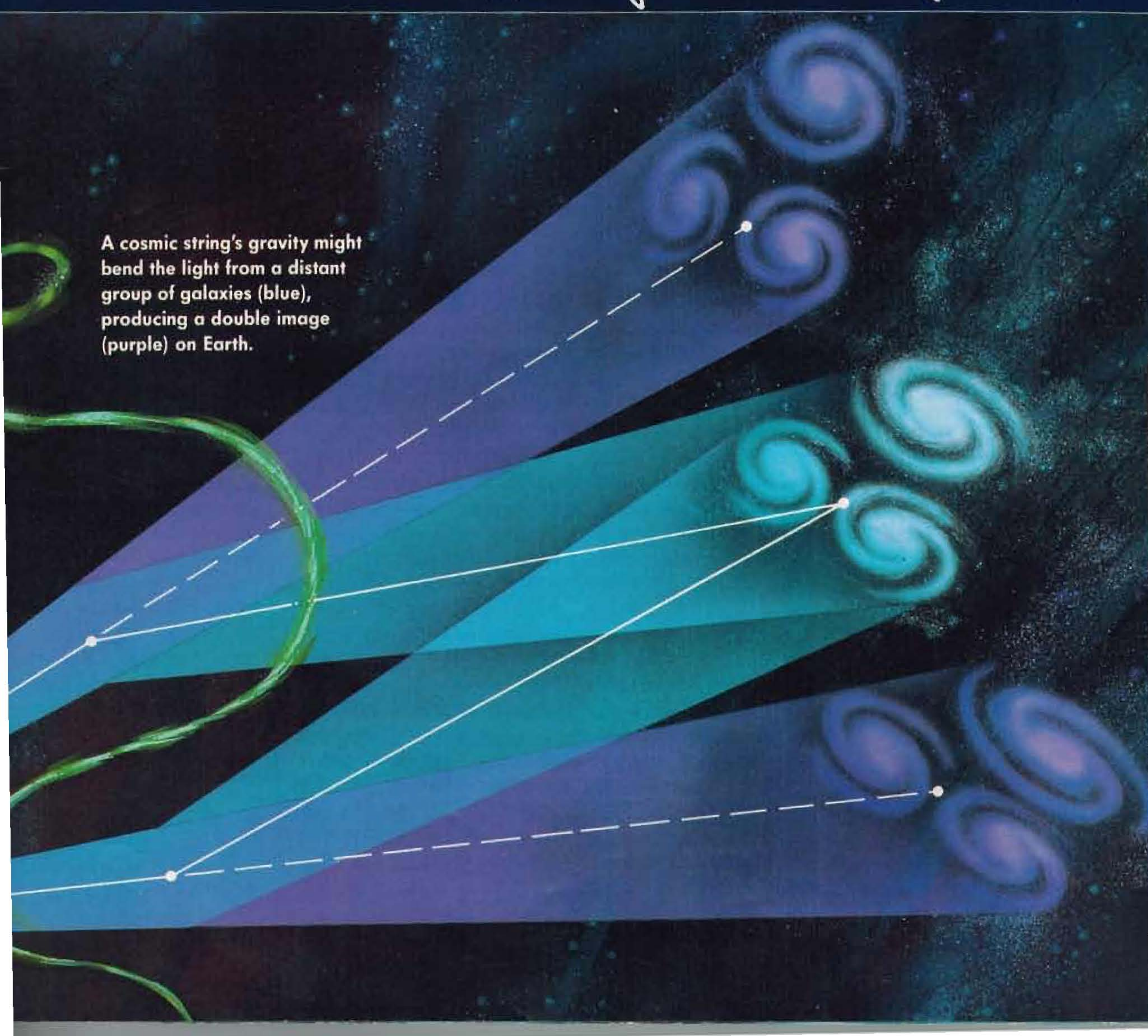


After a loop of cosmic string breaks off from its universe-spanning parent, it oscillates furiously, repeating the same cycle about a million times before it decays away. Albrecht and Turok's simulation of one typical cycle is shown here and on the following page.

DIAGRAMS BY GABOR KISS; ILLUSTRATION BY IAN WORPOLE chain, as opposed to a single pair of galaxies, would indicate that the gravitational lens was long and thin rather than pointlike.

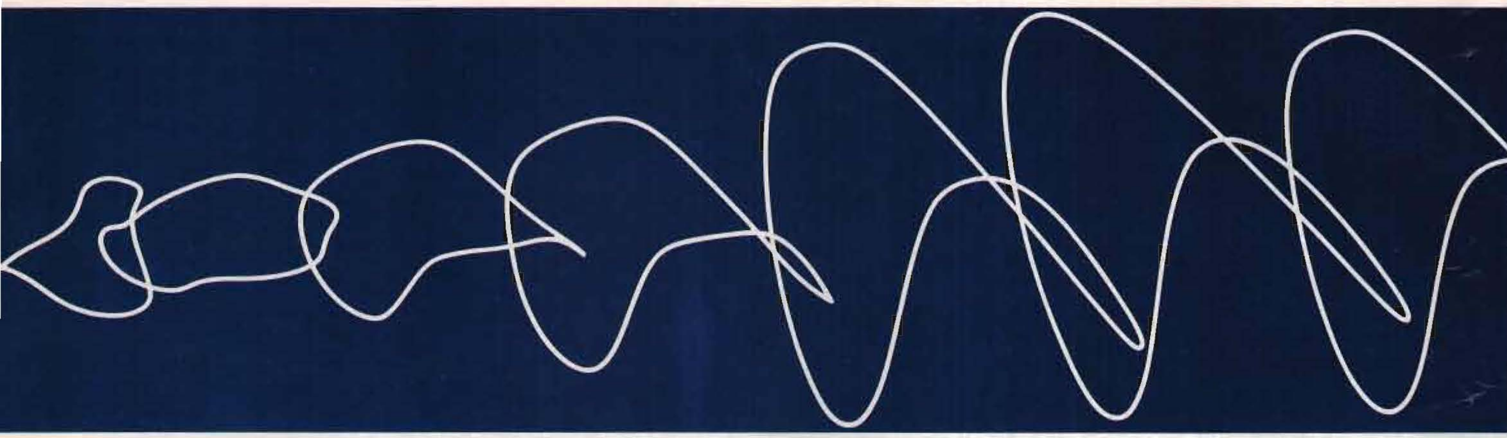
In recent months two University of Hawaii astronomers have reported, very cautiously, that they may have detected such a pattern. As so often happens in astronomy, the discovery was serendipitous. While studying the areas around distant quasars with a telescope atop Hawaii's Mauna Kea in the fall of 1985, Lennox Cowie and Esther Hu noticed something peculiar: four sets of twin galaxies were nestled close together. "At first we thought we had accidentally taken a double exposure," recalls Cowie.

Observations a year later established that three of the galaxy pairs are all 4.5 billion light-years from Earth. (The fourth pair is closer, about 2.5 billion light-years away.) The probability of real galaxy pairs forming such a close-knit family is extremely low. Moreover, the two members in each pair are virtually identical; when galaxies do come in pairs, they are rarely so similar. Cowie and Hu have suggested that this unusual grouping may be a mirage created by a loop of cosmic string, located somewhere between the galaxies and Earth, that is splitting each galaxy's image in two. The loop would be about 100,000 light-years across, the size of our Milky Way.



A cosmic string's gravity might bend the light from a distant group of galaxies (blue), producing a double image (purple) on Earth.

If strings do not explain the universe's structure, "it is likely to be something as bad—or worse."



The hypothesis is tentative; a similar announcement by a group of Princeton astronomers in 1986 was quickly shot down, to their chagrin. Cowie himself has reservations. "It could still be the accidental alignment of some binary galaxies," he cautions. "We're now taking deeper images of this sector to see if fainter galaxies are also being imaged twice." Other astronomers are examining the twin galaxies with infrared and radio telescopes in an effort to confirm whether the members of each pair are truly mirror images of each other.

But if the finding is confirmed, Cowie says, "it would be of monumental importance: it would be the first concrete evidence for grand unified theories." Physicists would at last have experimental verification for their most complex and ambitious imaginings.

The most convincing proof that strings exist and grand unified theories are right, as British astrophysicist Nick Kaiser and Albert Stebbins of Fermilab have pointed out, would be a particular glitch in the universe's microwave background. At a temperature of 3 degrees Kelvin (degrees Celsius above absolute zero), the microwave background is the residual glow of the Big Bang itself, a sea of microwaves very evenly dispersed throughout space. (In fact, that is how physicists know that matter in the early universe was so smoothly distributed.) As a string swims rapidly through this sea, the microwaves would ever so slightly be heated in the wake of the string and cooled in front of it. As a result, the microwave background would appear roughly one ten-thousandth of a degree hotter on one side of the string than on the other.

In maps of the microwave background this temperature jump would appear as a line tracing the position and shape of the otherwise invisible string. No other known process could produce such an image. Stebbins, who has graphically modeled the effect, says that a microwave detector currently aboard a Soviet satellite might conceivably spot the shift should a string enter its field of view. In the future more sensitive instruments will certainly be looking, too.

Strings are not the only cosmic defects that can be gleaned from the equations of grand unification; energy from the Big Bang could also have been trapped in singular points or within two-dimensional sheets called domain walls. A maze of domain walls, some investigators think, might have made a fleeting appearance throughout space and then disappeared, leaving behind the bubbly network of galaxies seen through telescopes. ("Life may be the product of imperfections," muses Marcelo Gleiser, a Fermilab researcher who is working on this domain-wall scenario.) A possible problem with domain walls is that they may be too energetic to create a universe that looks like our own.

The idea of pointlike defects, or monopoles, faces a similar problem. If any monopoles were created, theorists believe they must have been swept out of the visible universe when it underwent a brief spurt of superaccelerated expansion at the moment of creation. Otherwise, the combined weight of these particles—each as massive as an amoeba—would have caused the universe to collapse in a Big Crunch long ago. "Strings, on the other hand, cause no such harm," notes Vilenkin. Indeed, that is one reason why they have attracted the most theoretical attention.

It is far too early to say whether the notion of cosmic strings or of any other cosmic defects is true. "Strings are certainly not necessary," says Vilenkin. Nonetheless, "they're still worth studying because they might be there." Again black holes are an instructive precedent. Only a few decades ago black holes seemed more at home in science fiction stories than in astronomy textbooks; today their existence is almost universally accepted. Cosmic strings may one day become equally familiar.

If so, they will have brought cosmologists a good deal closer to a complete understanding of our cosmic beginnings. And they will have done so in spite of—or perhaps because of—properties that seem impossibly exotic today. "The laws of physics are simple and beautiful," says Vilenkin. "But when you work out the consequences of those laws, you often get very complicated results." ◻

DIAGRAMS BY GABOR KISS

Marcia Bartusiak's article "The Short Life and Violent Death of Sanduleak −69" appeared in the January issue.