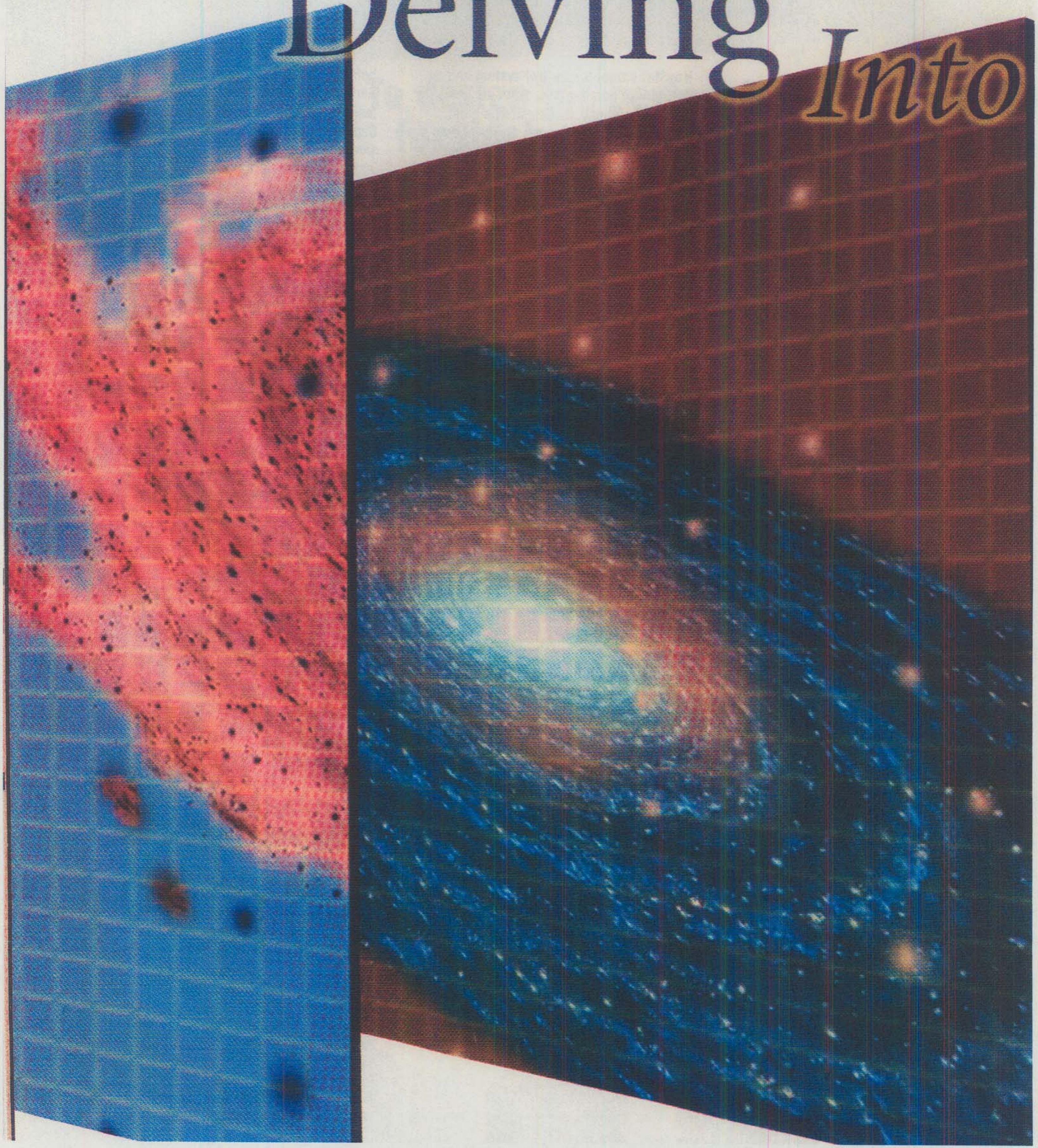
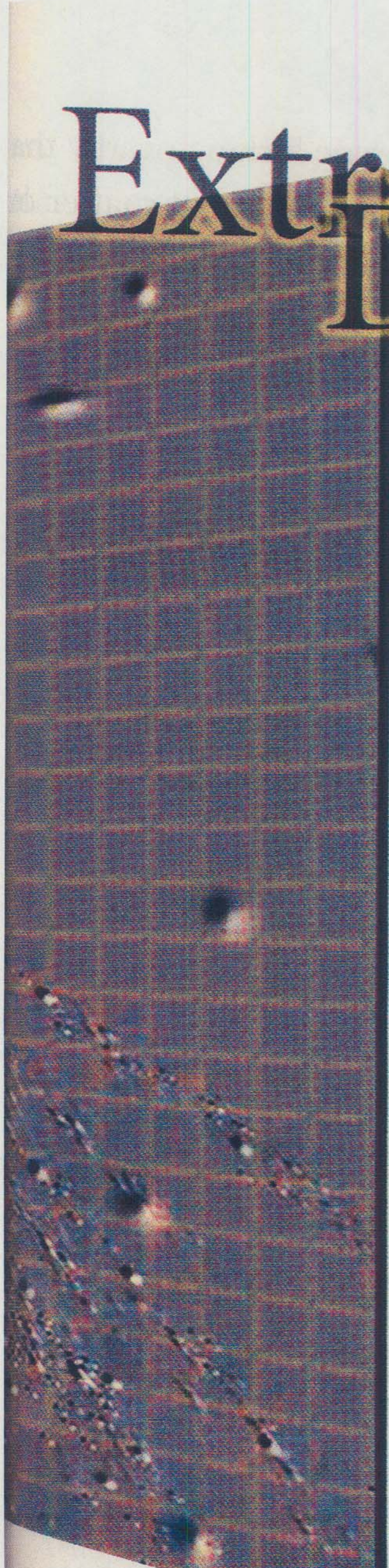
Delving *Into*



Extra Dimensions

It may sound like science fiction, but a proper explanation of the goings-on in our universe may rely on the existence of other universes lying beyond our view.



When you think about black holes, you probably breathe a sigh of relief that they're far, far away. In all likelihood, the nearest stellar-mass black hole lies well beyond the solar neighborhood, and the supermassive monster at the heart of our galaxy is safely tucked away at a distance of some 26,000 light-years.

But at this very moment the nearest black hole might be just a few kilometers over your head, created when a subatomic particle from space — a cosmic ray — smashed into a proton in Earth's atmosphere at near light speed. According to a recent estimate, cosmic-ray interactions could produce one microscopic black hole about every minute somewhere in the sky above.

BY ROBERT NAEYE

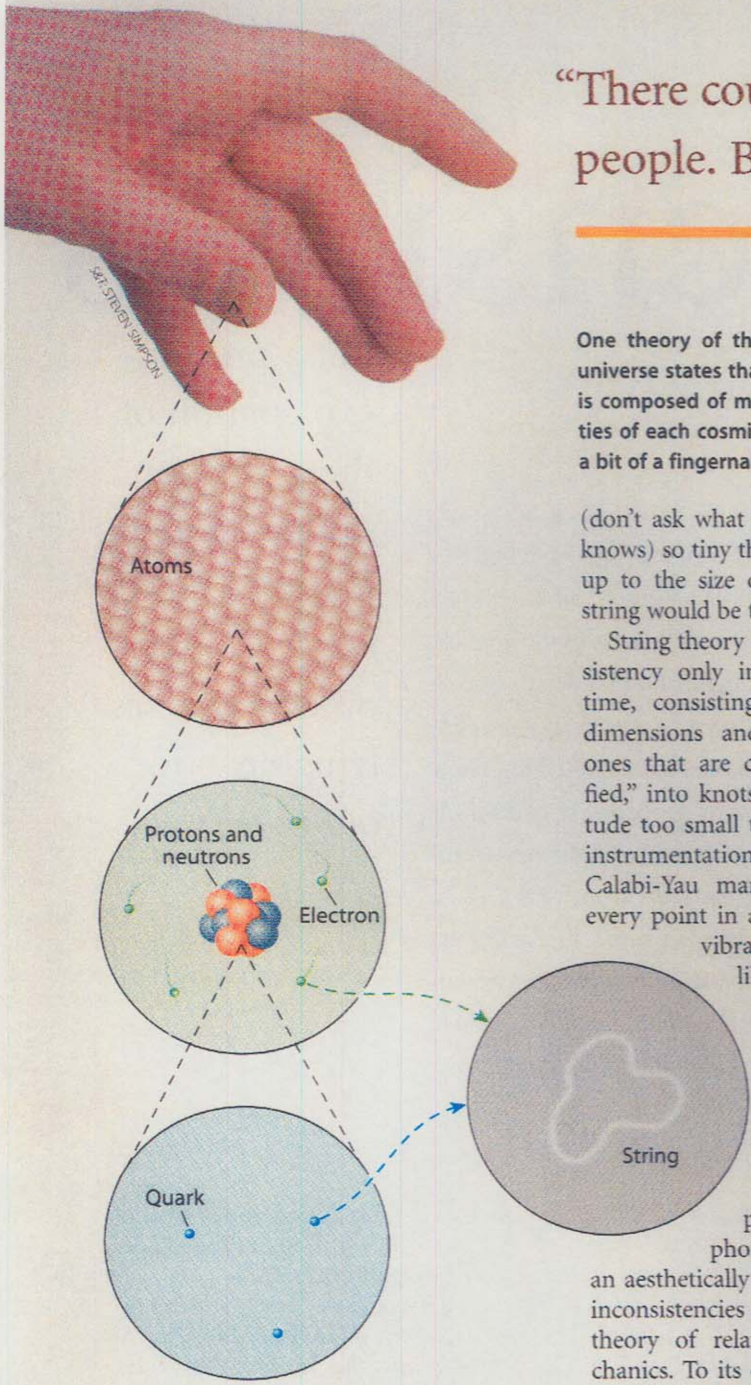
If you think the imagination of physicists has run amok, consider this: A parallel universe might be free-floating in hyperspace just 10^{-30} centimeter from you. This universe has its own panoply of particles, which we might "feel" as dark matter, though the two universes otherwise remain totally disconnected. But every trillion years or so the two universes collide and bounce, triggering what we call a Big Bang.

Sounds crazy? It might be just crazy enough to be true. It all hinges upon an exciting new idea that our universe has not just the familiar three dimensions of space and one of time, but additional dimensions of significant size.

The concept of extra dimensions represents an aesthetic allure impossible to resist for many scientists because it provides a geometric framework for solving some of astronomy's thorniest mysteries, such as the nature of dark matter and the enigmatic dark energy that's causing the universe's expansion rate to accelerate (*S&T:* September 1998, page 38). And unlike other seemingly outlandish ideas in modern physics, the existence of large extra dimensions could be confirmed by experiments or astronomical observations in the next few years. On the other hand, the recent flurry of research on extra dimensions could represent a colossal waste of intellectual energy, like the Ptolemaic concept of planets tracing epicycles.

The universe we live in may have spatial dimensions beyond our perception. Such hidden membranes, or "branes" — curled up within the standard dimensions of spacetime — may lie as close to us as the adjacent pages of a book. Artwork by Jon Lomberg.

"There could be a shadow brane lurking nearby that
people. But we could feel the gravity of matter on



One theory of the overall structure of the universe states that every subatomic particle is composed of minuscule strings. The qualities of each cosmic string define whether it's a bit of a fingernail or a neutrino.

The Road to M-Theory

To a scientist, "dimensions" are independent coordinates needed to locate a point or event in space. In everyday life we experience the three spatial dimensions of height, width, and depth, and one dimension of time. While the idea of extra spatial dimensions has fallen in and out of favor over the past century, it experienced a renaissance in the early 1970s with the emergence of string theory as the leading contender for a "theory of everything." According to string theory, all matter and energy consists of one-dimensional strings (don't ask what they're made of; nobody knows) so tiny that if an atom were scaled up to the size of the visible universe, a string would be the size of a tree.

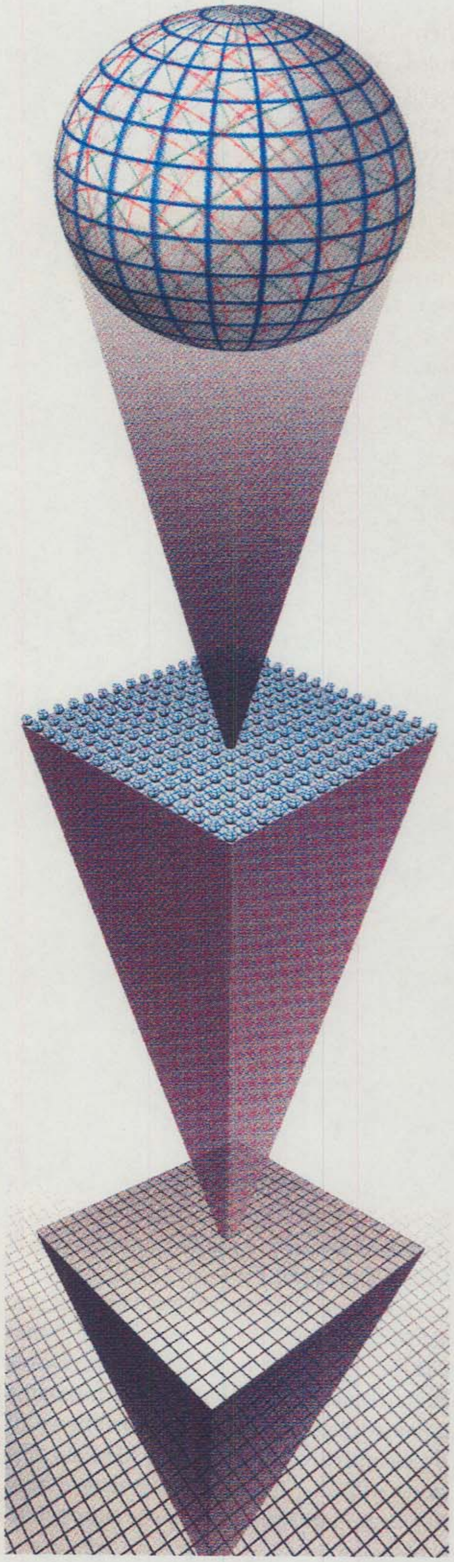
String theory enjoys mathematical consistency only in 10-dimensional space-time, consisting of the four "regular" dimensions and six additional spatial ones that are curled up, or "compactified," into knots many orders of magnitude too small to be detected by current instrumentation. These knots (known as Calabi-Yau manifolds) are attached to every point in a space-time grid. Strings vibrate in 10 dimensions, and, like different notes on a violin, the frequency of each string's vibration determines whether it's a photon, an electron, a neutrino, a quark, or some other particle.

To string theory's supporters, the universe's symphony of vibrating strings is an aesthetically beautiful way to reconcile inconsistencies between Einstein's general theory of relativity and quantum mechanics. To its detractors, string theory is a purely theoretical construct with no experimental evidence to support it. In fact, it would require a particle accelerator the size of the Milky Way Galaxy to probe the realm of strings and compactified dimensions — a project that even a billion Bill Gateses couldn't afford. "On the whole, string theorists study theories rather than the world," scoffs University of Michigan physicist Gordon L. Kane, expressing the skepticism of many physicists who heap scorn at string theory's inability to be tested or falsified by near-term experiments or astronomical observations.

In 1995 Edward Witten (Institute for Advanced Study), Petr Hořava (now at the University of California, Berkeley), and other physicists unified five competing versions of string theory into a new framework called M-theory. According to Witten, "M stands for magic, mystery, or membrane, according to taste." (Critics might prefer "mythical" or "mystical.") As if 10 dimensions weren't enough, M-theory adds yet another spatial dimension to science's conceptual palette. And besides one-dimensional strings, the abstruse mathematics of M-theory allows for the existence of higher-dimensional fundamental objects, which string theorists refer to as *membranes*, or branes for short.

M-theory has inspired a flurry of creative "braneworld" models that depict our universe as being "glued" to a 3-D brane embedded in higher-dimensional hyperspace. Physicists have little trouble describing this picture mathematically, but our 3-D brains aren't particularly well equipped to visualize this concept. Think of our universe as the 3-D analogue of a page in a book. Every planet, star, and galaxy we see is confined to the same page. But just as books contain a multitude of pages, the branes of an infinite number of parallel universes could be floating in higher-dimensional hyperspace. These other branes could lie a tiny fraction of a millimeter away from our brane in higher-dimensional "bulk" space and yet remain imperceptible to our best telescopes and experiments.

But string theory provides a mechanism by which our brane could interact with other branes, with profound implications for astronomy and cosmology. According to string theory, "open-ended" strings give rise to the vast majority of subatomic particles. Their endpoints, or legs, remain anchored to our brane, just as a cursor moves in only the two dimensions of a computer screen (though the strings are free to move about our brane). As a result, most particles and forces "feel" only the familiar three spatial dimensions, which explains why we we cannot see. It could have shadow galaxies, shadow stars, shadow this shadow brane. It would appear to us as dark matter." — STEPHEN W. HAWKING



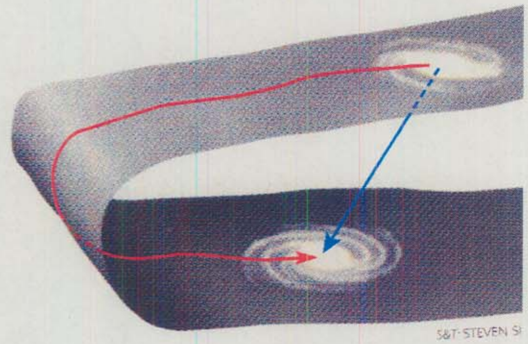
According to string theory, six additional spatial dimensions (besides length, width, and depth) have been "compactified" below our perception.

haven't detected these other dimensions. But strings can also form closed loops, lacking endpoints that attach themselves to our brane. The hypothetical quantum particles that transmit gravity, called *gravitons*, are closed loops and thus free to roam bulk space and travel from one brane to another.

This concept of roaming gravitons could explain the dark-matter mystery. Most of the dark matter that dominates the rotation of spiral galaxies and the motions of galaxies within clusters could in fact be normal matter on another brane. This matter emits gravitons that propagate onto our brane, thus transmitting the gravitational force from another universe to ours. Although other branes might have different forms of matter, forces, and even physical laws (or even a different number of dimensions), we might have gravity in common.

"There could be a shadow brane lurking nearby that we cannot see," explains University of Cambridge cosmologist Stephen W. Hawking. "It could have shadow galaxies, shadow stars, shadow people. But we could feel the gravity of matter on this shadow brane. It would appear to us as dark matter." Large accumulations of mass in both branes would tend to attract one another, which would explain why dark matter appears concentrated around clusters of galaxies and galaxy halos. We can't see matter from other branes (or higher-dimensional space) because the photons it emits can't travel to our brane.

Conversely, our universe could be folded upon itself in higher-dimensional space, like a crumpled page. A galaxy that appears billions of light-years away might lie less than a millimeter away in bulk space. The light from the galaxy would have to travel the full length of



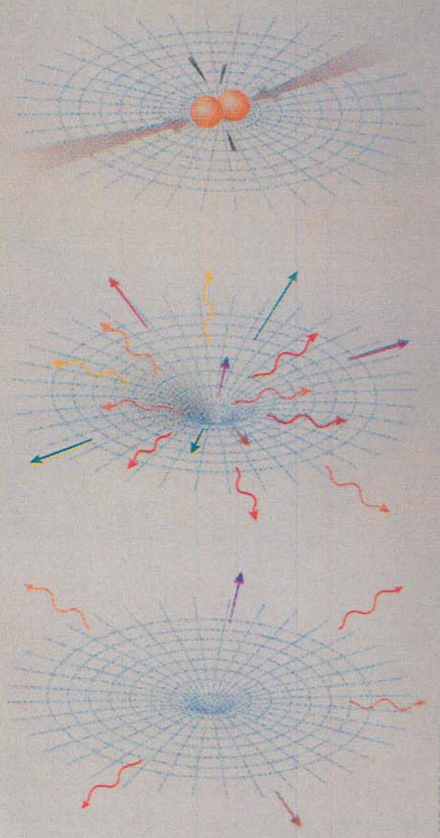
String theory indicates that gravitons, the hypothesized but still undetected particles of gravity, can travel freely between branes. Consequently, some of the effects of dark matter may actually be the result of the universe's branes being folded, allowing seemingly distant matter to be close to us in "bulk space."

creases in the fold, but gravitons from the galaxy would take a shortcut through the folds, like traveling through a wormhole. "In this picture, there is no dark matter. It only appears dark because it's on the other side of the fold," says Georgi Dvali of New York University. Compelling evidence for these ideas could surface in just the next few years if the Laser Interferometer Gravitational-Wave Observatory (LIGO) and other detectors (*S&T:* October 2000, page 40) register powerful sources, such as merging black holes, that have no visible counterparts.

Artificial Black Holes

String theory assumes but does not explicitly predict that the compactified extra dimensions are ridiculously small. In an influential 1998 paper, Nima Arkani-Hamed (now at Harvard), Savas Dimopoulos (Stanford), and Dvali considered the ramifications if some of these compactified dimensions are considerably larger; perhaps two of them could be as large as a millimeter in diameter.

At first glance the idea might seem preposterous, but it doesn't violate any known experimental result. The "ADD" paper (after the authors' initials) showed, "A tiny black hole will not gobble up Earth as it would evaporate in a puff of Hawking radiation



CERN's Large Hadron Collider will accelerate protons to nearly the speed of light and crash them head-on into each other. The collision should produce a mini black hole. However, the black hole will quickly evaporate in a burst of particles and radiation.

S&T: GREGG DINDERMAN

among other things, that such large extra dimensions could, in principle, resolve one of physics' most enduring mysteries: the pathetic weakness of gravity. After all, a toy magnet can lift a pile of paper clips even though the entire mass of planet Earth is pulling against it. Compared to the other fundamental forces of nature, gravity is 38, 35, and 31 orders of magnitude weaker than the strong nuclear force, electromagnetism, and the weak nuclear force, respectively.

Neither general relativity nor quantum mechanics provides a satisfactory explanation for the inherent feebleness of gravity. But if two of the extra dimensions are up to a millimeter in size, Arkani-Hamed, Dimopoulos, and Dvali point out that the strength of gravity on our brane will be diluted as gravitons spread into the additional volume of these extra dimensions. But at scales corresponding to the sizes of these extra dimensions, gravity could become as strong as the other forces — so strong that it violates Newton's inverse-square law. "According to this idea," says Dvali, "gravity is weak not because it is fundamentally weak; it is as strong as the other forces. But gravity *appears* weak because there are extra dimensions through which gravity can spread and become weak."

Unlike the tiny dimensions of string theory, the existence of ADD's large extra dimensions can be tested in the here and now. In fact, tabletop experiments at Stanford, the University of Washington, and elsewhere are looking for deviations in the inverse-square law of gravity at small scales. So far, these ongoing experiments rule out two extra dimensions up to 0.1 mm in size, but they do not rule out the possibility of three or more large extra dimensions, provided they are much smaller than 0.1 mm.

A spectacular confirmation of ADD's extra dimensions could come before the end of the decade with experiments at the CERN particle-physics laboratory near Geneva, Switzerland. There, physicists are building the $2 billion Large Hadron Collider (LHC), a 27-km-long underground ring where researchers will continuously shoot two beams of protons into each other at speeds a hair less than that of light. When LHC begins its experiments around 2007, it will be about seven times more powerful than the Tevatron accelerator at Fermilab, currently the most powerful accelerator on the planet. According to two papers published in mid-2001, one by Greg L. Landsberg (Brown University) and Dimopoulos, and the other by Steven B. Giddings (University of California, Santa Barbara) and Scott Thomas (Stanford), the LHC could produce microscopic black holes by the bushel.

Assuming that the other dimensions of the ADD model exist, the LHC's proton collisions will concentrate enough mass-energy into a small enough volume that gravity's extra strength will kick in, causing the smashed protons to collapse upon themselves to form minuscule black holes. "We now consider LHC and future accelerators to be black-hole factories," says Landsberg. "We'll just switch on the accelerator and see them from day one."

LHC's black holes will cram the mass of a large organic molecule into a volume one-thousandth that of an atomic nucleus. According to a quantum process that Hawking outlined in 1973, these mini black holes will evaporate into a shower of elementary particles in a mere 10^{-26} second, an existence so fleeting that the blink of an eye is an eternity in comparison. Landsberg, for one, thinks this shower of "Hawking-radiation" debris will be so unmistakable that distinguishing black-hole evaporations from other particle decays will be a "no-brainer."

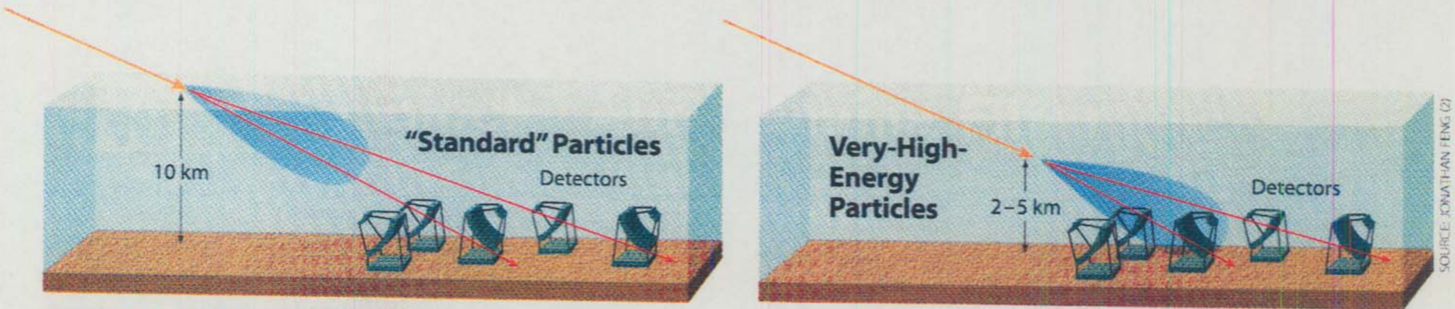
LHC will provide the "put-up-or-shut-up" test for ADD's large extra dimensions. "If the LHC doesn't prove this theory right, the idea is dead and it's time to move on," says Landsberg.

Dimopoulos agrees: "If we don't see the large dimensions at the energies of the LHC, I would personally give up."

Nature's Collider

In case you're worried about LHC becoming a Doomsday device, with mini black holes acting like tiny Pac-Men gone berserk, you can sleep soundly knowing that during the black holes' 10^{-26} second of existence, they simply don't have enough time to gobble up any surrounding material. "A tiny black hole will not gobble up Earth as some newspaper stories would have you believe," Hawking notes. "Instead, it would evaporate in a puff of Hawking radiation and I would win a Nobel prize."

As proof that these experiments are safe, Landsberg points to the fact that cosmic rays have been bombarding atoms in Earth's atmosphere for eons, and some cosmic-ray interactions are millions of times more energetic than LHC's collisions will be. "The very fact that we have not been made extinct by cosmic rays in some newspaper stories would have you believe," Hawking notes. "Instead, and I would win a Nobel prize."



SOURCE: JONATHAN FENG (2)

PIERRE AUGER OBSERVATORY

Mini black holes may be produced naturally, as highly energetic cosmic rays collide with atoms in our atmosphere. Detectors of the Pierre Auger Observatory in Argentina *(left)* should be able to pick out black-hole-generated particle air showers — a few each year — from those of "normal" cosmic rays. *Top left:* Protons and other heavy particles will collide 10 km up, producing a shower of muons, gamma rays, and positrons. The latter two products are further scattered by the atmosphere (blue teardrop), leaving only muons (red) to reach the detectors. *Top right:* Very-high-energy particles — powerful enough to produce mini black holes — will penetrate deep into the atmosphere, allowing the cone of telltale gamma rays and positrons to reach the detectors.

the billions of years of Earth's existence is the best proof that the LHC is completely safe to operate," he says.

If the other dimensions exist, cosmic rays should generate a microscopic black hole somewhere in Earth's atmosphere every minute, according to Jonathan L. Feng (University of California, Irvine) and Alfred D. Shapere (University of Kentucky), who explored the possibilities in the January 14, 2002, *Physical Review Letters*. Feng points out, "Cosmic rays are nature's collider, which provides us with the same collisions for free." If large extra dimensions do not exist, gravity will remain very weak at small scales, and even the most energetic cosmic rays won't have the oomph to produce black holes.

Current cosmic-ray experiments cover areas only the size of cities, making it improbable that they would register an unequivocal black-hole event. But that situation will soon change. An international consortium is currently building a giant cosmic-ray-detector array in Argentina called the Pierre Auger Observatory (see the March issue, page 39); a twin array will eventually be built in Utah. Auger's 1,600 individual particle detectors will be spread over an area the size of Rhode Island. Once the $54 million facility is up and running around 2004, Feng and Shapere predict that Auger might be able to discriminate several hundred black-hole evaporations per year.

If the Auger Observatory sees no black-hole events, the nondetection will place severe constraints on the sizes of ADD's extra dimensions. "Skeptics see this as an opportunity to place very stringent bounds that to one extent or another will exclude this crazy idea, so they can get on with the real world of four dimensions," says Feng. "These cosmic rays provide the most sensitive probe for some of these ideas. You either will see something or you won't. If you see something, that changes the whole way we think about physics and how many dimensions we live in. If you don't, then you put bounds on these new ideas. So whatever happens is progress."

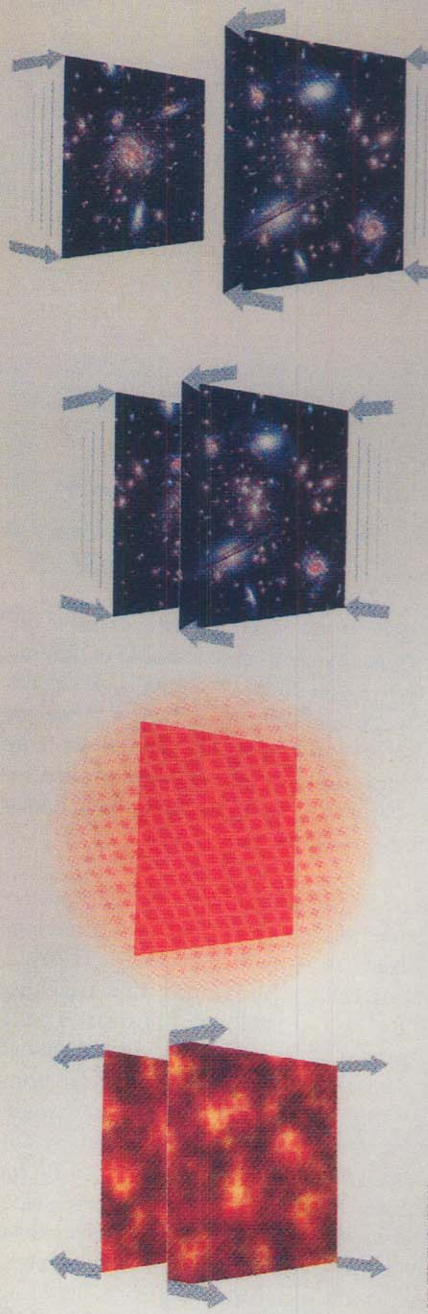
A Cyclic Universe

Other physicists are contemplating the ramifications of M-theory and large extra dimensions for the birth and evolution of the universe itself. In just the past year a new cosmological model has emerged that envisions an eternal cycle of Big Bangs and Big Crunches resulting from the interaction of two branes.

In the original incarnation of this cyclic model, developed in 2000–01 by Paul J. Steinhardt and Justin Khoury (Princeton), Neil G. Turok (Cambridge University), and Burt A. Ovrut (University of Pennsylvania), our universe existed for untold trillions of years as a cold, featureless brane nearly devoid of matter and energy. But about 14 billion years ago our brane collided with a parallel brane in bulk space — an event we call the Big Bang. The kinetic energy of the collision was converted into quarks, electrons, photons, and all the other particles we see today. Each brane began stretching after the collision, which to us looks like cosmic expansion. Steinhardt and his colleagues called their cosmology "the ekpyrotic model," after the ancient Greek word for "conflagration."

Steinhardt and Turok have since extended the model into a full-fledged cyclic model in which the two branes undergo an endlessly repeating cycle of collision-expansion-collision — driven by a new kind of force arising from quantum interactions between the two branes. As the branes stretch, they move apart and remain separated by about 10^{-30} cm in bulk space. During this phase the inter-brane force acts similarly to the mysterious dark energy that's causing our universe's expansion rate to accelerate. "In stark contrast to standard Big Bang cos-

"In stark contrast to standard Big Bang cosmology, the cyclic model actually predicts an accelerating universe after galaxies form." — Paul J. Steinhardt



S&T: STEVEN SIMPSON

Additional dimensions may explain how the Big Bang came about. When two branes collided 14 billion years ago, they scrambled all matter and energy and resulted in what we see as an expanding universe. Such a collision could happen repeatedly, starting a fresh universe each time.

mology," says Steinhardt, "the cyclic model actually predicts an accelerating universe after galaxies form."

After the branes have expanded, cooled, and thinned out over many trillions of years (the model doesn't yet specify precisely how long this takes), the interbrane force begins to pick up steam, drawing the branes closer together. As the branes approach, the stretching comes to a virtual halt, leaving the thinned matter and radiation. Over the next 10 billion years or so, the two branes move toward each other and finally collide, an event that can be likened to crashing cymbals on a gargantuan scale. The extra dimension momentarily collapses. When the two branes bounce apart or pass through each other, the new matter and radiation cause the branes to begin stretching anew.

The cycle repeats itself — again and again and again — ad infinitum. The cyclic model is reminiscent of oscillating-universe models, but with the twist of an extra spatial dimension that collapses instead of our familiar three dimensions. The initial burst of expansion from inflationary-universe models instead becomes episodes of slow, dark-energy-induced, accelerated expansion that flattens the geometry of space-time.

While colliding universes may seem like an unpleasant fate, the cyclic model has considerable philosophical appeal. If the universe expands forever, stars will burn out, matter will decay, and the universe is destined to degenerate into a cold, empty void (*S&T:* August 1998, page 32). But in the cyclic model, each brane collision reinvigorates our universe with new potential.

Steinhardt, who helped develop the idea of inflation in the early 1980s, asserts that the cyclic model is consistent with all astronomical, cosmological, and particle-physics observations, and it's "as fully developed as the standard model even though it is very recent." Steinhardt also notes that if the cyclic model works, it avoids the singularity problem of standard Big Bang cosmology, which has yet to explain how a universe can emerge from a point of infinite temperature and density. While the model provides a credible alternative to Big Bang/inflation cosmology, most cosmologists have yet to embrace it.

Inflation theory dictates that exponential expansion produces a spectrum of gravitational radiation with long wavelengths that crisscross the sky today, leaving a distinctive circular pattern in the polarization of the cosmic microwave background (CMB). In contrast, the cyclic model predicts a purely radial polarization pattern. Last September, University of Chicago cosmologists reported the first detection of polarization in the CMB (*S&T:* December 2002, page 20), and it had a radial pattern. But their South Pole observatory doesn't have the sensitivity to distinguish the circular component predicted by inflation. The European Space Agency's Planck satellite, scheduled for a 2007 launch, might be sensitive enough to do this measurement, but its design has not yet been finalized. NASA has future plans for a CMB polarization satellite that should be able to determine which model, if either, is correct.

Will extra dimensions be the key concept to unlocking the mysteries of dark matter, dark energy, and the origin and evolution of the universe, or will the idea be consigned to the ash-heap of history, like the 19th-century idea of a universal ether? Thanks to a new generation of observatories and experiments, we should soon know whether large extra dimensions truly exist, or whether they are mere figments of the fertile human imagination. As University of Chicago cosmologist Michael Turner says, "If we discover extra dimensions, it will be the biggest breakthrough of the early 21st century. If we don't find them, it will be a real egg in the face. Scientists 100 years from now will ask, 'What were they smoking?'"

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