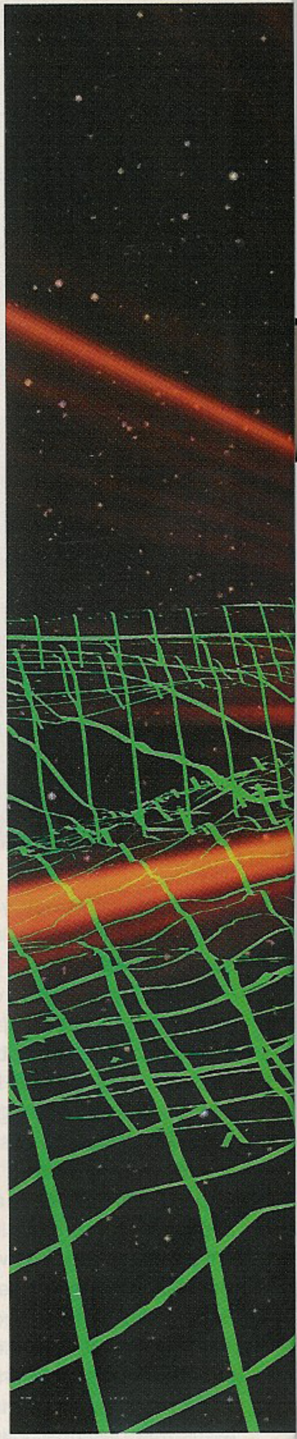
NICE GOING, EINSTEIN

With his general theory of relativity, he tried to explain gravity—and left an even bigger mess for today's physicists to clean up

BY **LAWRENCE KRAUSS**



One of the great paradoxes of physics is that while gravity was the first force in nature to be described physically and mathematically—Isaac Newton worked out its basic laws more than 300 years ago—it may be the last to be understood. Generations of physicists have remained stumped by the utter strangeness of gravity: Not only is it the weakest of the four natural forces, but it is also the only one that appears to be directly related to the nature of space and time. Still, theorists steadfastly continue to wrestle with the problem, dreaming up extra dimensions or, as in Mordehai Milgrom's case, proposing new versions of Newton's classic equations.

Much of today's confusion about gravity is the fault of that brilliant troublemaker Albert Einstein. In his greatest work, the 1915 general theory of relativity, he demonstrated that, unlike the other three forces, gravity is intimately coupled to the fabric of space. The remaining ones—electromagnetism and the strong and weak nuclear forces—merely describe how objects move through space. Gravity relates to the properties and dynamics of space itself, which can respond to the presence of matter by curving, expanding, and contracting. What we observe as a gravitational pull between objects is actually, according to Einstein, the result of an underlying curvature in three-dimensional space. This curvature becomes apparent only when the objects are very massive, so it is not surprising that it went undetected until 1919, when Sir Arthur Eddington and his team announced they had verified Einstein's prediction that the sun's gravitational field would bend light.

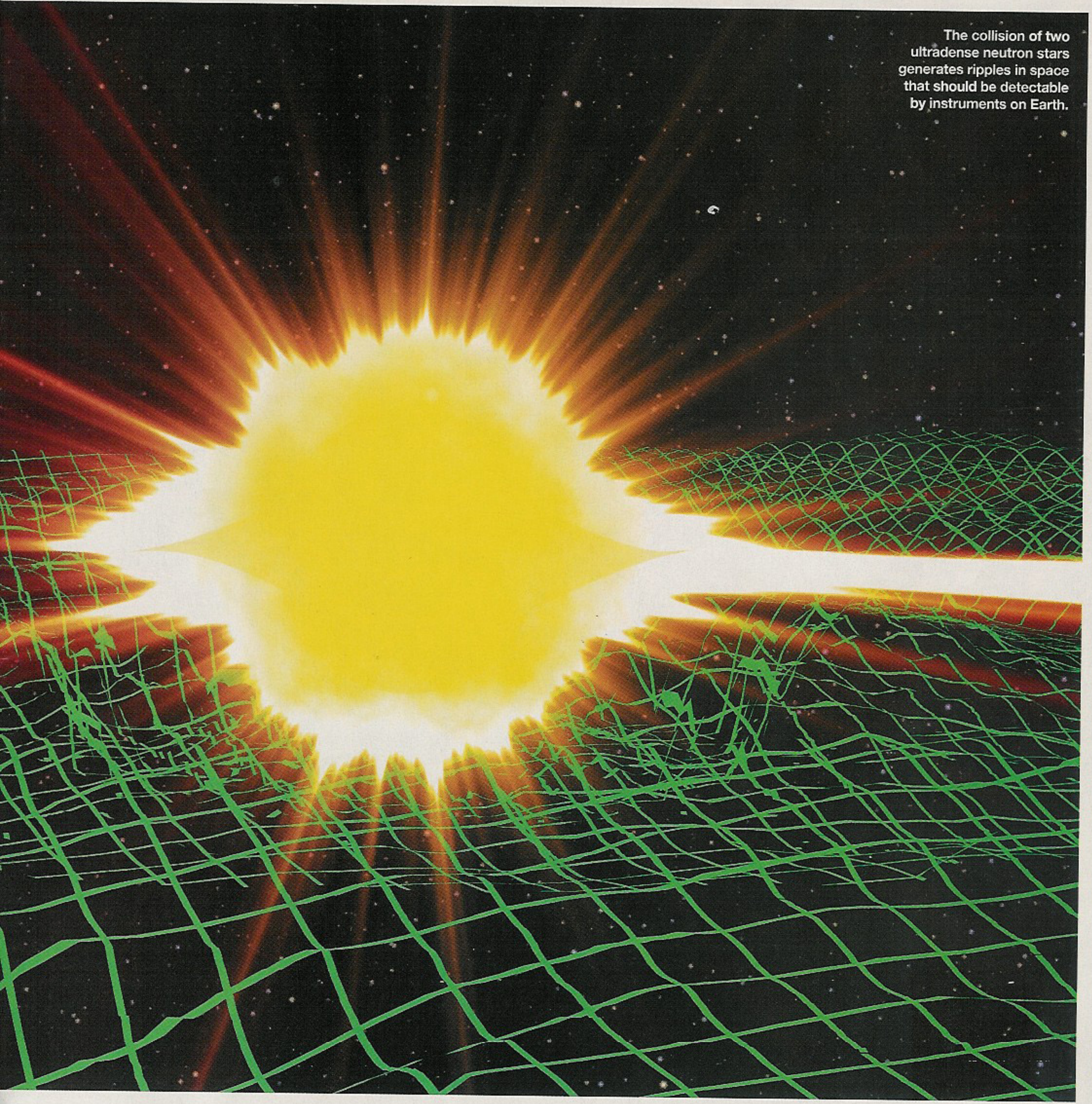
The uniquely geometric nature of gravity has made it frustratingly difficult to contain within the same framework as the laws governing subatomic phenomena, namely quantum mechanics. This problem has prompted physicists to consider extreme solutions, including the possibility that our three-dimensional universe is but the tip of a vast cosmic iceberg (see the July 2006 *Discover,* page 50). In this interpretation, the three dimensions we experience are merely an illusory front for a universe that may have between 6 and 22 additional hidden dimensions.

As far back as the 1920s, some physicists proposed that if gravity is related to a curvature in our three-dimensional universe, other forces in nature might result from curvature in as yet unseen dimensions. Alternatively, in response to various astrophysical puzzles, other physicists, including Milgrom and his collaborator, Jacob Bekenstein, have argued that Newton's laws, which describe motion in our solar system wonderfully well, break down on the scale of galaxies.

The other major conundrum that drives physicists to distraction is why gravity is so much weaker than all the other forces. Physicist Richard Feynman illustrated the disparity with the following description: If a man jumps out of a tall building, it may take gravity 200 feet to pull him down to the ground, but electromagnetism halts him in a fraction of an inch. The electric repulsion between electrons surrounding separate atoms in his body and the concrete is so intense that it stops the falling body without so much as denting the concrete.

A great deal of current research in theoretical physics is motivated by a yearning to understand why gravity is so feeble. Yet it is precisely this weakness that makes investigating new theories of gravity so difficult. Producing detectable gravitational effects requires a great deal of matter or energy. For instance, just as accelerating charges produce electromagnetic waves (like visible light), accelerating masses should create gravitational waves—ripples in space. Studying such waves would tell us a lot about how gravity works. But because gravity is weak, only the most colossal cosmic events are likely to make waves that we can detect. LIGO, the Laser Interferometer Gravitational Wave Observatory, is a pair of three-mile-long gravitational-wave detectors in Washington and Louisiana that cost $365 million and took 11 years to build, and yet they may just barely be able to pick up signals from the ultraviolent collisions that give birth to massive black holes.

Perhaps only when we study huge agglomerations of matter, in



The collision of two ultradense neutron stars generates ripples in space that should be detectable by instruments on Earth.

galaxies or clusters of galaxies, will we spot the elusive phenomena that can take us beyond Einstein and Newton. This is why so much current research on gravity focuses on astrophysics and cosmology, the domains in which gravity is king.

As always, nature is mystifying. Astronomical evidence gathered over the last 30 years suggests that most of the mass in our galaxy—indeed, in all galaxies—is invisible to telescopes and may comprise new forms of elementary particles. In the past decade, we learned something even more astounding: that the overriding gravitational influence in the universe comes not from matter but from a mysterious form of energy that suffuses the emptiness of space. This dark energy, as it is known, exerts an antigravitational impulse that appears to be causing the expansion of the universe to accelerate. We have no idea why it exists or why it has the value it does.

Each time we open a new window on the universe, we find surprises. When we turn on the world's largest particle accelerator—the Large Hadron Collider near Geneva—next year, will we open a portal into other dimensions? When we measure the forces between distant galaxies more accurately, will we find deviations from Newton's laws, as Milgrom suggests? I wouldn't bet on either of these possibilities, but there is one bet that is easy to make: Whatever surprises nature has in store for us, they are likely to involve gravity. ■