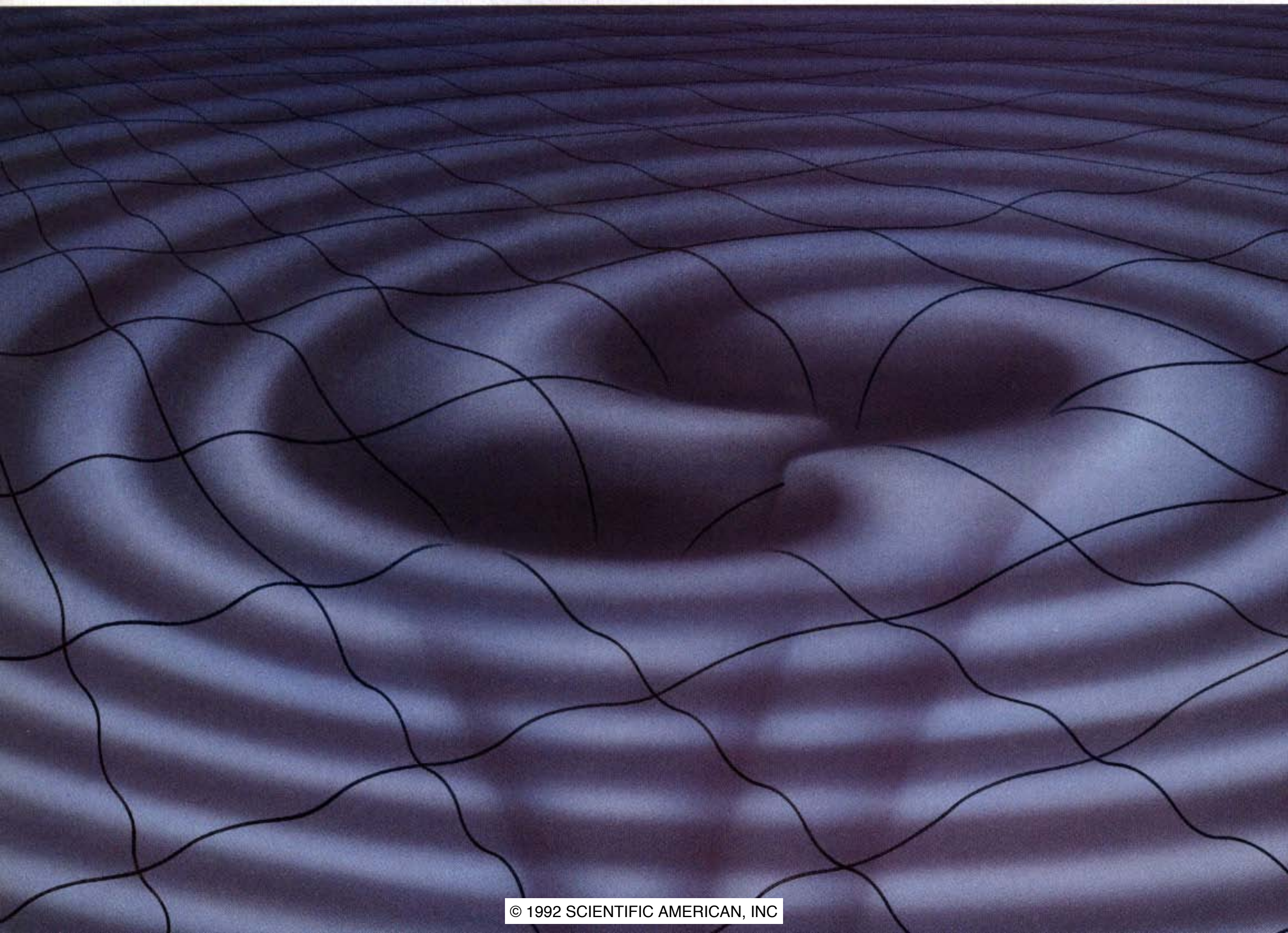
CATCHING THE WAVE

by Russell Ruthen, *staff writer*

Space is not just the nothing between the earth and the stars. Nor is it simply the void between the electron and the atomic nucleus. It is a ubiquitous medium more resilient than rubber, more rigid than steel.

Nearly 75 years ago Albert Einstein realized that space takes its shape from the mass it contains. Our sun is too meager to warp space much. But a black hole is the ultimate space bender. A small black hole holds three times more mass than our sun in a sphere a million billion times smaller in volume. Were two black holes to collide, they would curve, knot and twist space in ways that theorists have only begun to imagine. These cataclysmic collisions would provide the ultimate test for Einstein's most sophisticated ideas, his theory of general relativity.

After decades of research—and many partial attempts—physicists are ready to construct an unusual telescope that might finally allow them to observe such space-warping events. But unlike any other telescope, their instrument is not sensitive to electromagnetic radiation: not light, radio waves, gamma rays or any part of the spectrum. It is designed, instead, to detect gravitational waves, small changes in the shape of space.

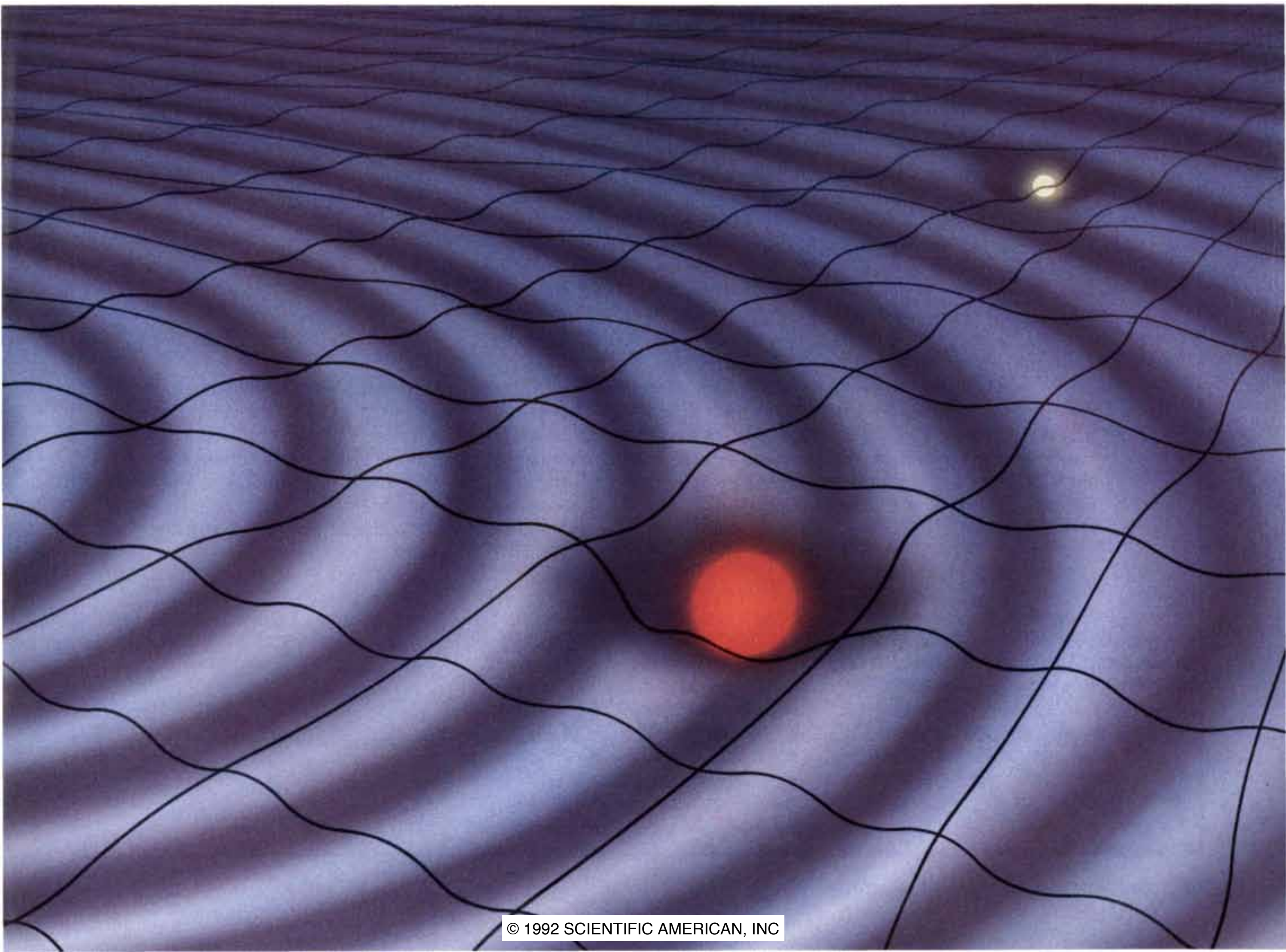


Scientists hope to explore the nature of gravity and the frontiers of the universe by detecting gravitational waves. The U.S. government has promised them $211 million to build two kilometer-size detectors. Will they succeed?

Astronomers have seen the effects of gravitational waves, but no instrument built so far has been sensitive enough to detect the waves directly. According to Einstein's theory, gravitational waves propagate outward from their source like ripples traveling across a pond. As the waves expand into space, they weaken. But gravitational waves, unlike electromagnetic radiation, will not be blocked by stars or cosmic debris or—when they eventually reach it—the earth.

With a sensitive detector, it should therefore be possible to observe gravitational waves as they compress and expand both space and matter by an infinitesimal amount. For example, if the gravitational waves from two colliding black holes in a distant galaxy were to pass through a detector one kilometer long on the earth, the length of the detector would change by less than a billionth of a

TWO BLACK HOLES produce gravitational waves as they spiral around each other. Here space is represented as a strong, elastic sheet, like the fabric of a trampoline. Any object with mass, such as the stars below, will exert a strain on space, which will distort the fabric. Each black hole stretches the fabric to infinity. As the black holes move around each other, some of the distortions travel outward as gravitational waves.



billionth of a meter. That's a distance about 1,000 times smaller than the diameter of an atomic nucleus.

A team of physicists from the California Institute of Technology and the Massachusetts Institute of Technology headed by Rochus E. Vogt hopes to catch the first wave—and more. During the next five years, his group plans to erect two facilities on opposite sides of the U.S. that will house the world's largest interferometers. Each device will generate intense laser beams that will bounce back and forth along two paths four kilometers long and interfere with each other at a point. If a gravitational wave of sufficient strength passes through the device, the distance that the light beams must travel will change slightly, altering the way the light beams interfere.

A bill appropriating the first funds for construction was signed by President George Bush in October 1991. Known as the Laser Interferometer Gravitational-Wave Observatory (LIGO), the project is expected to cost a total of $211 million. If the LIGO team achieves its goals and current predictions are trustworthy, the interferometers should be sensitive enough to observe the gravitational waves emitted from a pair of colliding neutron stars. If so, the project may produce the first direct confirmation of the existence of gravitational waves by the end of the decade. But, most important, it will permit researchers to peer into the universe in a way that differs radically from any previous observation.

By detecting gravitational waves instead of electromagnetic radiation, researchers should be able to detect both bright objects such as exploding stars and dark objects such as black holes. If luck is with them, they may discover unknown celestial bodies or even gravitational waves emitted at the moment of creation. "I believe profoundly," Vogt exclaims, "that LIGO will become most famous not for neutron star binaries and black holes and everything but for the things we can't even think of yet."

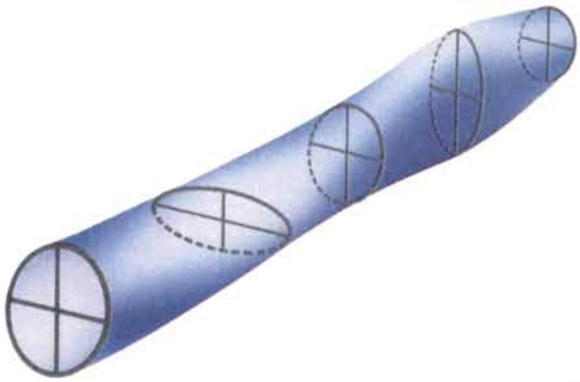
Many scientists do not share the optimism of the LIGO team, and the need for the project is hotly debated. Although theorists can calculate the strength of the gravitational waves that would emerge from two orbiting black holes, they do not know how many such systems exist. Neutron star binaries are the only source of gravitational waves for which both the strength and number can be predicted with confidence. No one can be sure, however, that LIGO will be sensitive enough to observe them.

Einstein's Glitch?

Then again, no one was certain that gravitational waves existed until recently. Even Einstein had doubts. In 1916 he proposed in his theory of relativity that gravitational waves, and indeed the force of gravity, are manifestations of the bending of space. For decades, theorists argued passionately over whether gravitational waves were real or were merely a glitch in Einstein's theory. The debate provoked Sir Arthur Eddington, whose observations confirmed general relativity, to comment that gravitational waves "propagate ... at the speed of thought!"

During the 1950s, theorists finally reached a consensus that gravity waves did indeed exist. In 1957 Joseph Weber, a physicist at the University of Maryland, set out to build the first gravita-

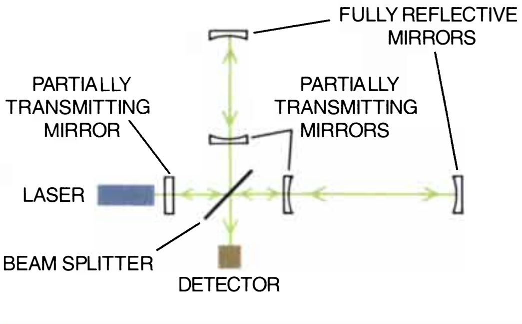
Detecting Gravitational Waves

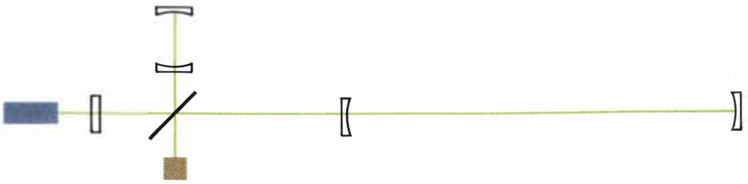


It should be possible to observe gravitational waves because they shrink and stretch space and matter. Imagine, for example, a gravitational wave that passes through a long cylinder [*see diagram at right*]. As the wave travels from one end of the cylinder to the other, it does not distort the cylinder equally in all directions. The wave can compress matter in one direction while expanding it in a direction perpendicular to the compression.

The LIGO team hopes to detect gravitational waves using a sophisticated interferometer similar to the one depicted below. Laser light passes through the recycling mirror and hits a beam splitter. The light then enters one of two Fabry-Perot cavities, each of which consists of a partially transmitting mirror and a fully reflective mirror. The light bounces many times within the cavities and then leaks out through the partially transmitting mirrors. The cavities and the recycling mirror are included to store the light, boosting the power and sensitivity of the device.

The light leaked from each cavity hits the beam splitter and is recombined. Some of the recombined light is reflected back into the interferometer by the recycling mirror. The rest of the recombined light reaches the detector, which measures the intensity of light. If a strong gravitational wave passes through the detector, the compressions and expansions of the instrument (*bottom right*) will affect the way the leaked light recombines at the beam splitter. As a result, the detector records the passage of the gravitational wave as a change in light intensity.





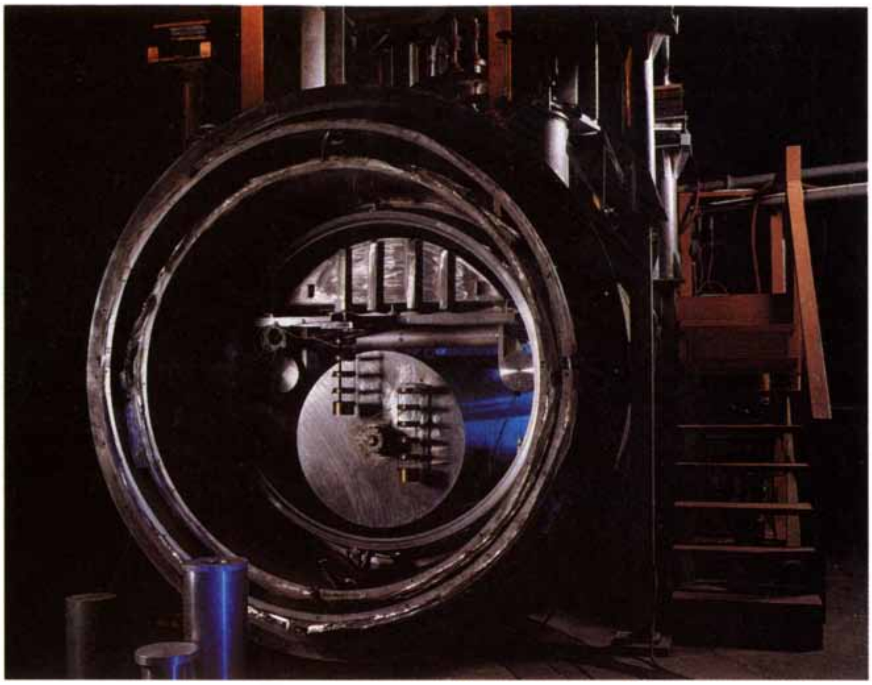
tional-wave detector. Its key component was a cylindrical bar, weighing several tons, which was suspended from cables in a vacuum chamber and isolated as much as possible from outside vibration. After considering all sources of gravitational radiation known at the time, Weber determined that most of them would emit gravitational waves at a frequency around 1,000 cycles per second. He therefore engineered the size, shape and composition of the bar so that it would resonate like a tuning fork to waves of that frequency.

If a passing gravitational wave caused the bar to expand and then contract, a transducer would convert the tiny motions into electrical signals that could be measured. The strength of the wave would be related to the strain (the change in length divided by the length) induced in the bar. After constructing several prototypes, Weber settled on a two-meter-long bar detector that was capable of measuring strains of one part in 10^{16}, equal to a change in length of about two tenths of a millionth of a billionth of a meter.

During the past 35 years, Weber has reported several events that he claims are "evidence for gravitational waves." His most famous results, in 1969, appeared to show that gravitational waves were radiating from the center of our galaxy. Since Weber's report, many laboratories around the world have built sophisticated bar detectors to confirm his results, but none has revealed statistically significant evidence for gravitational waves.

Nevertheless, Weber's pioneering work inspired others to search for gravitational waves. Soon after Weber began publishing his results, Rainer Weiss, who is now one of the principal investigators for LIGO, began teaching a course in relativity at M.I.T. His students were excited by Weber's experiments, and Weiss searched for a way to explain the results in a simple way. It was then that he seized on the idea of using light beams to detect gravitational waves. (At the time, Weiss was unaware that Weber and several others had also thought about using light to detect gravitational waves.)

The first gravitational-wave detector that used light beams was built in 1971 by Robert L. Forward and his colleagues at Hughes Research Laboratories. It was based on the interferometer, which American physicist Albert A. Michelson had invented 90 years earlier to disprove the existence of the cosmic ether.



BAR DETECTOR was constructed to sense gravitational waves. If a strong wave were to pass through the detector, it would produce a strain on the bar—an aluminum cylinder suspended in a vacuum chamber. The strains and the resulting vibrations could then be detected. The apparatus, in a laboratory at Stanford University, cools the bar to four kelvins to reduce extraneous vibrations caused by heat.

The modern form of Michelson's device consists of a laser, a beam splitter, two mirrors and a photodetector arranged to form a cross. The laser is placed at, say, the west end of the cross; the detector rests at the south end; the mirrors are positioned at the east and north ends; and the beam splitter sits in the middle. The laser beam first passes through the beam splitter, which redirects half the light toward the north mirror and guides half toward the east mirror. Both mirrors reflect the light back along its previous path to the splitter. There the beams are recombined and directed onto the detector.

What the detector measures depends on the distances between the beam splitter and the mirrors. At certain distances, when the light waves emerge from the splitter, headed for the detector, the crests of the light waves that came from the north are in sync with the crests of the light waves from the east. As a result, the light waves reinforce each other, increasing the intensity of the recombined beam that falls on the detector. But if the distances between the beam splitter and each mirror are then changed by half the length of the light waves, the crests of the light waves from the north emerge from the splitter at the same time as the troughs of the light waves from the east. The two cancel each other out, and no light reaches the detector.

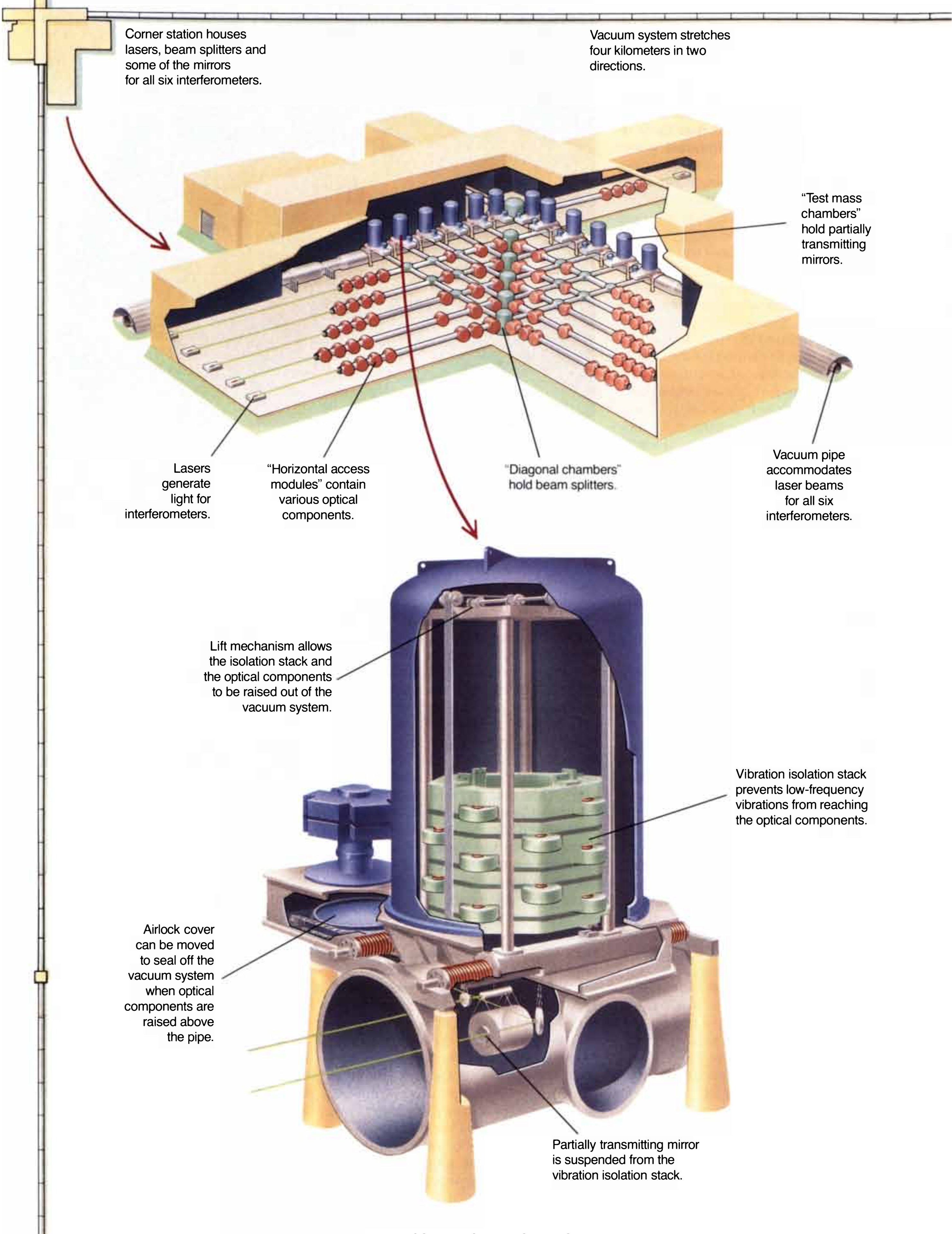
For the purpose of detecting gravitational waves, the mirrors are positioned so the light waves cancel each other out. But should a gravitational wave pass through the interferometer, it will change the distances between the components slightly. As a result, some light will hit the detector, which will then record a change in intensity that will be proportional to the strength of the gravitational wave [*see box on opposite page*].

Most experimentalists believed interferometers should ultimately be more sensitive to gravitational waves than bar detectors are. An interferometer reacts at the speed of light, whereas the components of a bar detector respond at a speed equal to that of sound.

An Astronomical Detector

Although those first interferometers were about 100 times more sensitive than Weber's bars, none has yet produced evidence of a gravitational wave. Ironically, the only convincing observation so far that gravitational waves exist came not from gravitational-wave detectors but from radio telescopes. In 1974 astronomers Joseph H. Taylor, Jr., and Russell A. Hulse, then at the University of Massachusetts at Amherst, found a "neutron" star known as PSR 1913+16, which has since provided strong, quantitative evidence for gravitational waves. Like other neutron stars, PSR 1913+16 has somewhat more mass than the sun, compressed into a sphere

The LIGO Facility



Corner station houses lasers, beam splitters and some of the mirrors for all six interferometers.

Vacuum system stretches four kilometers in two directions.

“Test mass chambers” hold partially transmitting mirrors.

Lasers generate light for interferometers.

“Horizontal access modules” contain various optical components.

“Diagonal chambers” hold beam splitters.

Vacuum pipe accommodates laser beams for all six interferometers.

Lift mechanism allows the isolation stack and the optical components to be raised out of the vacuum system.

Vibration isolation stack prevents low-frequency vibrations from reaching the optical components.

Airlock cover can be moved to seal off the vacuum system when optical components are raised above the pipe.

Partially transmitting mirror is suspended from the vibration isolation stack.

Mid-station holds fully reflective mirrors for three two-kilometer interferometers.

End station contains fully reflective mirrors for three four-kilometer interferometers.

less than 10 kilometers in diameter. At that density, matter exists most comfortably as neutrons, hence the name.

PSR 1913+16 is a kind of neutron star called a pulsar. It has a very strong magnetic field that rotates with the star. The field accelerates charged particles in the vicinity of the star, generating beams of radiation that emerge from each of its magnetic poles. The beams spin around with the star, shining into space like a lighthouse beacon. By observing them, Taylor and Hulse discovered that PSR 1913+16 is rotating at the rate of about 16.9 times a second with a regularity that rivals that of an atomic clock.

What makes PSR 1913+16 even more unusual is that it orbits once around a companion star every eight hours. It reaches a top speed of 400,000 meters per second, only 750 times slower than the speed of light. In addition, the distance between the pulsar and its companion is 100 times less than the distance between the earth and the sun.

In essence, the pulsar is a precise clock orbiting rapidly through a severely warped region of space—the distortions caused by the great mass of the companion. These conditions are ideal for observing relativistic effects. Taylor explains that according to Einstein's theory of relativity, the orbital period should be "gradually decreasing as the system loses energy in the form of gravitational waves."

Since 1974 Taylor and his colleagues have been observing the decay of the orbital period. Their measurements agree with the predictions with an uncertainty of less than 0.5 percent. "Remarkably, we now have data that give us confirmation of this tiny effect that Einstein suspected would never be observed," Taylor remarks.

Unfortunately, the gravitational waves emitted by PSR 1913+16 are far too weak to be detected by Weber's bar, extant interferometers or even the proposed LIGO. Nevertheless, the discovery of PSR 1913+16 encouraged physicists to continue to think about what objects in the universe might produce sufficient gravitational radiation for earthbound instruments to detect.

One of the leading theorists of that group—and a key adviser to the LIGO team—is Kip S. Thorne. In the 1970s and 1980s he and several other theorists from around the world demonstrated that the universe should contain many different kinds of sources of gravitational waves. But they were frustrated in their attempts to make quantitative predictions. In all cases, they were missing at least one piece of important information that made it impossible to predict either the strength of the source or how many sources existed.

A decade ago, for example, theorists believed the most plausible source of gravitational waves that could be detected on the earth would be a supernova, the explosion of a massive star. They estimated that millions of supernovas occur throughout the universe every year. Those sheer numbers gave them the assurance that many stars would explode in relatively nearby galaxies.

But that alone did not guarantee detectability. Critics noted that astrophysicists simply do not know the detailed dynamics of supernovas and that the strength of gravitational waves produced by a supernova would depend on whether or not the collapse of the star was asymmetric. According to theory, a strong source of gravitational waves requires a massive, compact object that must be nonspherical, like a football, a cylinder or a barbell. Most important, the source must move rapidly in such a way as to accentuate the nonspherical component. For example, a football-shaped star that spins rapidly about its long axis produces no gravitational waves. But if the same star rotates end over end, it will be a strong emitter.

Caught Up in the Wave

Thorne, Bernard Schutz of the University of Cardiff and their colleagues have now identified neutron star binaries as the one type of potential source of gravitational waves whose strength can be unequivocally predicted from fundamental principles of physics and whose number can be estimated from astronomical observations. A neutron star binary is like a massive barbell rotating end over end. Over hundreds of millions of years, the two stars will spiral toward each other until they collide and merge. In the final moments before coalescence, the individual stars will be separated by a distance of about 20 kilometers and be moving at speeds comparable to that of light.

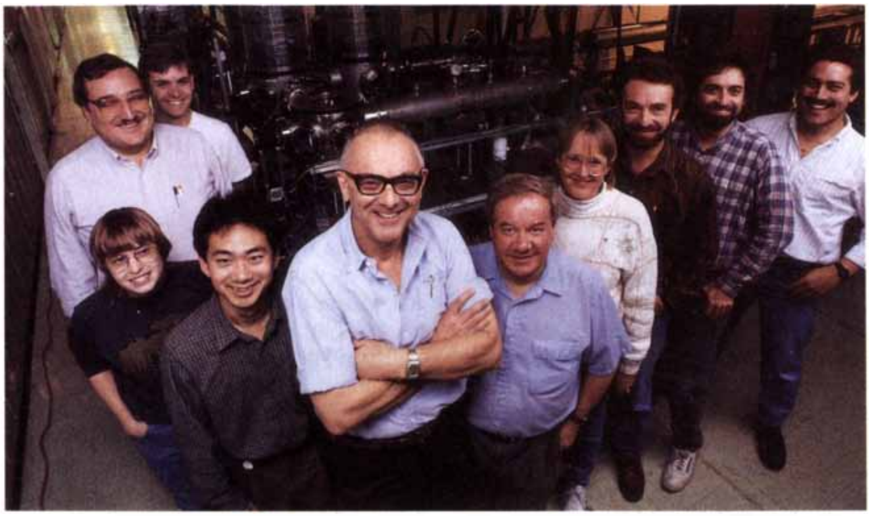
The gravitational waves from a neutron binary in a galaxy 650 million light-years away would produce a strain on the earth as large as four parts in 10^{22}. The frequency of the gravitational waves would equal twice the rate at which the neutron stars spiral around each other. A few minutes before the neutron stars coalesce, they should rotate about five times per second. Then, in their final throes, they should accelerate to more than 500 rotations per second. The frequency of the gravitational wave will therefore increase from 10 to 1,000 cycles per second.

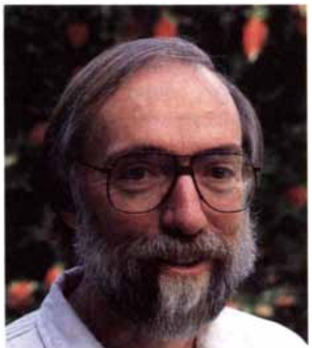
Neutron star binaries are rare in the universe and difficult to detect from their electromagnetic radiation. Astronomers have catalogued more than 400 neutron stars, but they have confirmed only four pairs of orbiting neutron stars in our galaxy. From these four, astrophysicists have figured out approximately how many neutron stars collide in the universe every year. Ramesh Narayan and his colleagues at the Harvard-Smithsonian Center for Astrophysics and E. Sterl Phinney of Caltech have independently estimated that a few pairs of neutron stars are likely to merge every year within about 650 million light-years of the earth.

In theory, then, if scientists construct LIGO so that it measures strains of four parts in 10^{22}, over a year they stand a good chance of detecting the gravitational waves from a few neutron star binaries. In practice, researchers would need to build at least two detectors at separate distant sites so that they could distinguish local disturbances from gravitational waves. They would have to erect another detector at a third site to determine the location of the source in the sky.

If LIGO snares a burst of gravitational waves from a neutron star binary before the turn of the decade, the event will make Thorne the winner of a bet he made with Jeremiah P. Ostriker of Princeton University in 1981. At stake is a case of "good red wine." Thorne contended that gravitational waves would be detected by the year 2000; his eminent colleague agreed that gravitational waves exist, but he believed Thorne had overestimated the strengths of astronomical sources of gravitational waves. Ostriker has not changed his mind. Does Thorne still expect to win? "I think it will be nip and tuck," he concedes.

Indeed, the history of LIGO has been one of fits and starts since Thorne touched off a contentious race with





Top: Members of the Caltech team, including LIGO director Rochus E. Vogt (arms folded in the center) and physicist Ronald W. P. Drever (to the right of Vogt). _Bottom left:_ The M.I.T. group, including physicist Rainer Weiss (seated at the right). _Bottom right:_ Caltech theorist Kip S. Thorne.

Weiss's group at M.I.T. to be the first to detect gravitational waves with an interferometer. In 1979, a year after Taylor and Hulse presented the first convincing evidence for gravitational waves, Thorne convinced the physics faculty at Caltech to enter the field of gravitational-wave detection. To lead the effort, the Caltech physicists recruited Ronald W. P. Drever, who had worked on bar detectors and interferometers at the University of Glasgow.

In response to Caltech's newfound enthusiasm for detecting gravitational waves with interferometers, the National Science Foundation (NSF) stepped up its funding. It began supporting gravitational-wave research at both Caltech and M.I.T. at the level of about $1 million a year. Drever and Weiss began to compete to build more sensitive and sophisticated interferometers.

The sensitivity of the devices can be enhanced by boosting the power of the lasers and by increasing the distance between the mirrors and the beam splitter. But the sensitivity can be compromised by several noise sources that arise because of small changes in the frequency of the laser light or small vibrations that move the mirrors and other optical components. An increase in laser power and the length of the beam can reduce some kinds of noise sources while exacerbating others.

To increase the sensitivity of the interferometer, Weiss worked on devices in which laser light bounces between two mirrors many times along different paths. This system, known as an optical delay line, effectively increases the length of the interferometer. Meanwhile Drever developed a scheme that utilized "Fabry-Perot cavities." In that system, laser light bounces between two mirrors along the same path to boost the power of the interferometer.

Weiss experimented with an interferometer whose two L-shaped "arms"—the length between the mirrors and the beam splitter—were 1.5 meters long. Drever, meanwhile, built and operated a 40-meter interferometer.

With the Caltech group appearing to be taking the lead, Weiss decided in 1981 to "do something dramatic." To attract the attention of the NSF and draw funding to M.I.T., he began a detailed study of the design and costs of a kilometer-scale interferometer. But he also aroused the interest of Thorne and Drever, who wanted Caltech to remain at the forefront.

The NSF settled matters by merging the M.I.T and Caltech groups in a "shotgun wedding" that marked the official beginning of the LIGO project. To manage the research, the NSF set up a steering committee that consisted of Thorne, Drever and Weiss. "That turned out to be a fatal error," Weiss says. The three physicists had protracted arguments about how a large-scale interferometer should be designed and managed.

In 1986 the NSF sponsored a workshop to review the plans for the LIGO project. During the workshop, 55 scientists and engineers debated the merits of LIGO before a panel of eight physicists, who had expertise in either investigating gravitational waves or managing large science projects. The panel strongly endorsed the scientific goals of the LIGO project, and it asked that the NSF fund the construction of LIGO.

But sensing problems in the management of LIGO, the advisory group also recommended that the NSF appoint a director for the project. A year later Rochus Vogt accepted the position. Vogt, a distinguished professor of physics and a former vice president at Caltech, was displeased with the progress of the M.I.T. and Caltech teams. He tried "to build a bridge between M.I.T. and Caltech" and pushed them through a painful transformation.

Drever, Weiss and their co-workers had been accustomed to doing experimental physics on a modest scale. They enjoyed their independence and their freedom. But Vogt realized that LIGO was not tabletop physics but big science. He needed to focus the team strictly on the task of developing LIGO. "As an R&D project to build the best possible, small L-shaped detector, it was great," he comments. "As an R&D project to prepare building the four-kilometer LIGO, it was a disaster."

In 1987 Vogt decided to delay plans to start construction of LIGO and insisted the team do more research until he was confident it could reach its goals. He also decided to concentrate on development of the Fabry-Perot interferometer and stop work on the delay-line system—a decision that Weiss reluctantly supported.

Noise Control

The LIGO team spent the next two years analyzing prototype components, including a thorough review of all conceivable sources of noise. According to LIGO's deputy director Stanley E. Whitcomb, the greatest concern at low frequencies is seismic noise, which is caused by vibrations that are transmitted from the ground to optical components. At high frequencies, the problem is photon "shot" noise, the result of small fluctuations in the power of the laser beams. The main obstacle at intermediate frequencies is suspension thermal noise, which arises because all structures vibrate slightly in proportion to their temperature.

The researchers first derived models that described each noise source and verified each model in tests on Caltech's 40-meter interferometer. Then they projected their results to predict the effect each noise source would have on the sensitivity of the four-kilometer LIGO. "In this business every sin is unforgivable," Vogt declares. "If you make one mistake, you are wiped out."

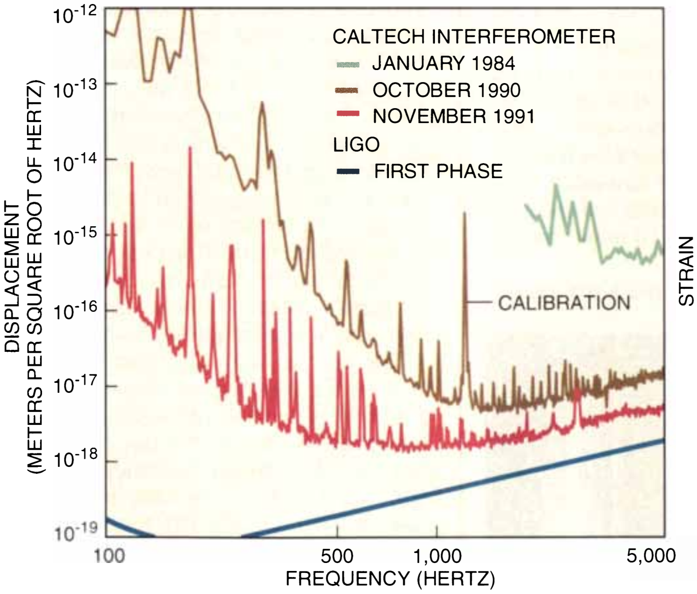
At the end of 1989 Vogt and his team decided they were ready to present the NSF with a construction proposal. As it is now envisioned, LIGO will consist of two facilities at widely separated sites. Each facility will contain an L-shaped vacuum system whose arms will be four kilometers long. The two facilities could eventually accommodate a total of nine interferometers that would operate simultaneously. The idea is to install interferometers gradually over a period of years, starting with the simplest systems and adding more advanced designs. Vogt explains, "The worst thing that we can do is to build a gold-plated Cadillac that has every sophistication built in from the start."

Around 1997, if all goes according to plan, the LIGO team will install one four-kilometer interferometer in each facility and an additional two-kilometer interferometer at one of the sites. With the three detector systems, the team believes it can rule out false signals that might be mistaken for gravitational waves. The team projects that this initial installation will be able to measure a strain of about three parts in 10^{21}, which may be 10 times too insensitive to detect the gravitational waves from neutron star binaries.

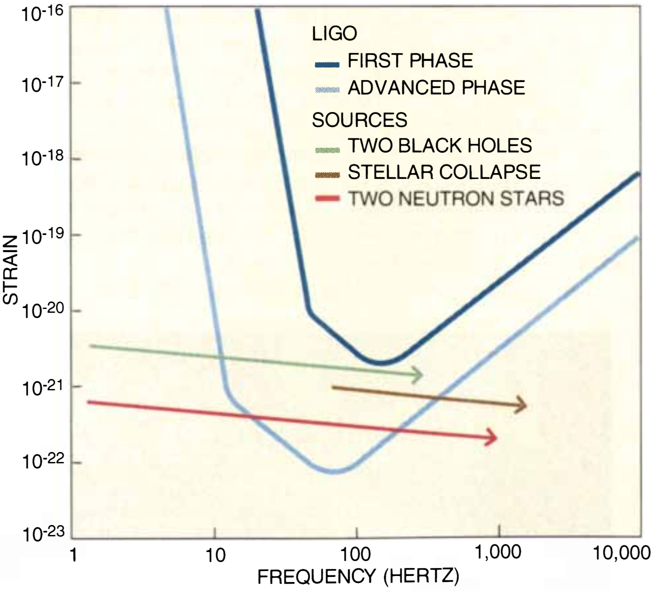
After a search for gravitational waves at that sensitivity, the LIGO designers plan to install several advanced detection systems that are currently being developed. They claim that these advanced systems will boost the sensitivity to the magic number of four parts in 10^{22}—the value needed to have a good shot at detecting neutron star binaries. By the time they install these detectors, they hope that a third kilometer-size detector will be built by one of the groups in Europe, Japan or Australia [*see box on next page*]. The third detector will allow them to determine the location of sources of gravitational radiation in the sky.

LIGO must still face the vagaries of funding and politics, however. In May 1990 the National Science Board approved its construction, but the following November Congress appropriated only $500,000 for continued engineering and design work. In March 1991 a subcommittee of the House Committee on Science, Space and Technology reviewed the project. It listened to the testimony of Vogt, J. Anthony Tyson of AT&T Bell Laboratories and others.

The opposition to LIGO was spearheaded by Tyson, whose research includes gravitational-wave detection. He argued that the early LIGO would probably be 100 times too insensitive to detect neutron star binaries. "In my judgement it is premature to commit to a full-scale LIGO," he said, recommend-



DISPLACEMENT SPECTRUM shows how the sensitivity of the Caltech interferometer has improved in recent years and how it compares with the projected sensitivity of LIGO. The interferometer's ability to detect gravitational waves depends on both the displacement spectrum and the nature of the waves. For a short pulse of gravitational radiation having a particular frequency, the smallest detectable change is approximated by multiplying the displacement at that frequency by the square root of that frequency. The narrow peaks do not reduce the sensitivity of the device significantly.



STRAIN SPECTRUM shows LIGO's projected sensitivity and three plausible sources of gravitational waves. (The projection allows for an adequate signal-to-noise ratio to rule out false events.) The red line indicates the strength and frequency range of the waves that could be measured on the earth if two neutron stars, 650 million light-years away, spiral together. The brown line shows the predictions for a star collapsing asymmetrically 100 million light-years away. The green line represents two coalescing black holes, 10 times larger than the sun, 650 million light-years away.

ing instead that construction of LIGO be postponed until the researchers demonstrated greater control over noise sources using the Caltech interferometer. The House Committee agreed: in June it continued to endorse "the expenditure of funds for research activities or design studies" but advised against authorization of funds for construction of LIGO.

The NSF, Caltech and M.I.T. retaliated by lobbying members of the Senate. They argued that LIGO had been strongly endorsed by physicists who had conducted peer reviews of the project. They also claimed that Tyson had underestimated the sensitivity of LIGO.

The LIGO advocates argued they were prepared to build the facility. They felt that a smaller version of LIGO would not be cost-effective, would slow the development of the technology and would greatly reduce the possibility of detecting gravitational waves.

For now, the advocates seem to have carried the day. Last September Congress passed a bill appropriating $23.5 million to begin construction of LIGO. But the project has not seen the last of the opposition. Many physicists feel that LIGO—like other "big science" projects, such as the Superconducting Supercollider—should not be a national priority. Astronomers fear that money spent on LIGO will indirectly reduce funds for astronomy, despite arguments by Vogt and others that LIGO does not divert funds from other research, because it is a line item in the NSF budget.

As plans stand, though, the LIGO team will create the final engineering diagrams for the twin facilities during the coming year and select two sites that are widely separated on the continental U.S., ideally ones that are flat, large and quiet both acoustically and seismically. The team has received 19 proposals from 17 states that wish to give one of the facilities a home.

The cost of the sites—indeed, even that of the interferometers—pales before that of the vacuum system. All the components of LIGO must be maintained under vacuum conditions to prevent scattering of the laser beams by gas molecules. Each LIGO site will require steel pipes that enclose a volume of 9,000 cubic meters, making it the world's largest vacuum system. The cost of the system, the related structures and buildings will consume more than 90 percent of the LIGO budget.

"I think LIGO is kind of a long shot, in the sense that it's probing uncharted territory," Joseph Taylor warns. "But that's why you do science—because you don't know all the answers ahead of time."

Entering the Age of Gravitational Astronomy

By observing gravitational waves, scientists hope to investigate some of the most mysterious events in the universe: the explosions of massive stars, the interactions between neutron stars and the collisions between black holes. To record useful information about gravitational-wave sources, astrophysicists expect that they will need at least three kilometer-size facilities located at different sites around the world. The U.S. has appropriated $23.5 million for LIGO, which consists of two four-kilometer facilities.

The approval of LIGO has raised hopes that funding may be forthcoming for similar projects in other countries. At the moment, the U.S. leads the field of gravitational-wave detection, but Germany, Britain, France and Italy are not far behind. Japan has started an ambitious program.

Each gravitational-wave facility would house one or more devices known as interferometers. These devices are sensitive to small movements that would be produced when the components of the interferometer interact with a strong gravitational wave. The sensitivity of the instrument is related to its length. By operating three interferometers simultaneously, scientists can determine the approximate location of gravitational-wave sources in the sky. The approximations should improve as the number of facilities and the distance between each increases.

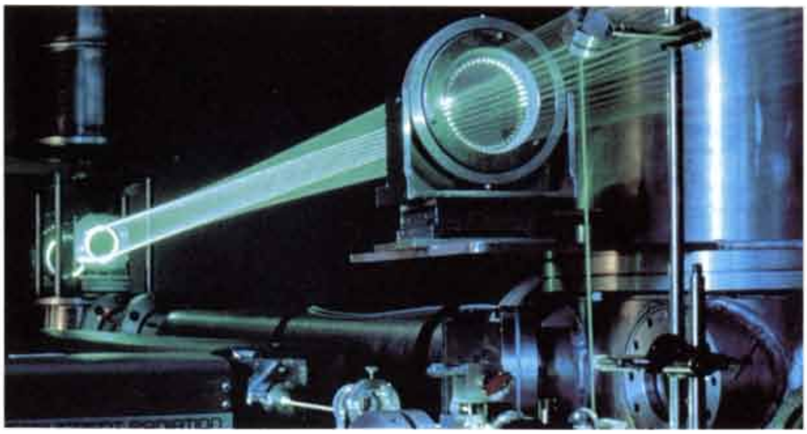
Researchers in Germany and Britain have agreed to build a three-kilometer interferometer. Although the project has received scientific approval in both countries, the German government has not yet appropriated funds, and British agencies are not prepared to invest heavily in the project.

Karsten Danzmann is the co-director for the effort to build the German-British interferometer, and he also heads a team that is reconstructing a 30-meter interferometer at the Max Planck Institute for Quantum Optics in Garching. "I consider the approval of LIGO a big help for the approval of the European plans," he comments. "It still seems a real possibility to complete the European and American detectors at about the same time and to start the age of gravitational astronomy."

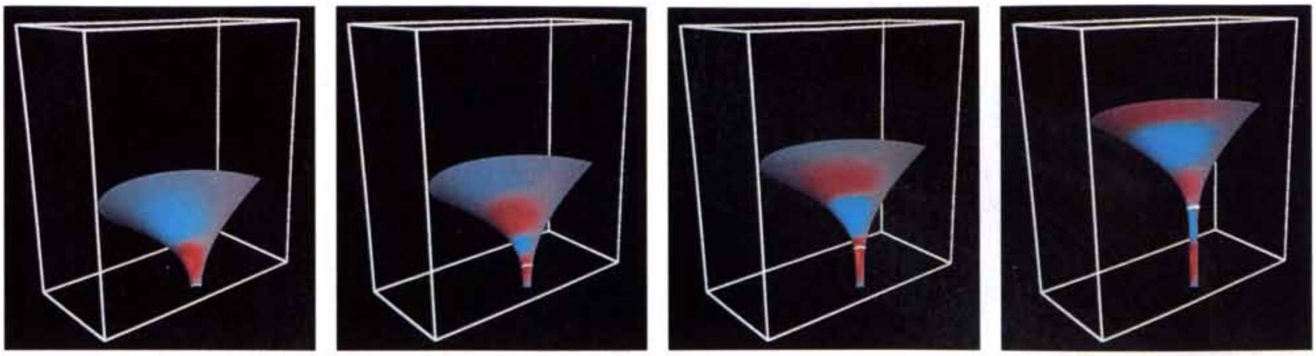
The German and British groups hope to team up with their French and Italian colleagues, who have plans for their own three-kilometer interferometer. In the spring French and Italian officials will decide whether to fund the project. According to Alain Brillet, co-director of the French-Italian collaboration, the project will not be granted "anything like $23 million in 1992, but the go-ahead for LIGO is a strong incentive for accelerating the decision."

Japanese researchers have quickly become strong competitors in the field. They recently built a 10-meter interferometer at the Institute of Space and Astronautical Science (ISAS). In April 1991 Japan began a four-year, $5-million project to construct a 20-meter interferometer at the National Astronomical Observatory and a 100-meter device at the ISAS. Nobuki Kawashima, director of the program at ISAS, says the 100-meter interferometer will be built to avoid the "engineering risks" involved in jumping from a 10-meter device directly to a kilometer-size instrument.

LIGO director Rochus Vogt comments: "The time is right to pluck the apple."



LASER LIGHT bounces between mirrors in a demonstration of the delay-line system for the 30-meter interferometer in Germany.



GRAVITATIONAL WAVE interacts with a black hole in a supercomputer simulation. The black hole curves space, which is represented by the off-white funnel. The red and blue regions represent gravitational waves. The region below the white band indicates the interior of the black hole. In the sequence of images above (*from left to right*), a gravitational wave approaches the black hole and enters, causing the black hole to generate new waves. The images are based on simulations conducted by David Hobill, Larry Smarr and David Bernstein of the University of Illinois.

Ultimately, the proof of LIGO's worth will be in what it reveals about the universe and the nature of gravity. Simply confirming the existence of gravitational waves once and for all would be an accomplishment that could justify the entire enterprise. But that verification would be only the beginning of a series of experiments that would further confirm—or challenge—prevailing theory.

Physicists should, for example, be able to determine such basic properties as the speed of gravitational waves. If the waves travel at the same speed as light, as predicted by theory, a burst of gravitational waves should arrive at the same time as a burst of electromagnetic radiation from the same event.

Beyond the First Wave

Thorne readily admits that LIGO is after bigger game than neutron star binaries: at the top of his wish list are black holes. Although astronomers have very little knowledge about how many black holes might exist, let alone how many black hole binaries might exist, "most pundits expect that if LIGO can look through the whole universe, it will see the coalescence of black hole binaries at a rate of many per year," Thorne suggests.

Two black holes, like two neutron stars, will spiral toward each other and produce a gravitational signal that rapidly increases in amplitude and frequency. A gravitational signal from a binary system, as Schutz has shown, contains information about the eccentricity and inclination of the orbit, the masses of the objects and the absolute distance to the source. And the eventual collision of two black holes will provide an extraordinary opportunity to test the theory of relativity. "For the first time, we may really see what a black hole looks like experimentally," Thorne asserts.

Einstein's theory has a perfect record in predicting how space and time react to masses that are relatively small and moving slowly. But theorists equipped with Einstein's equations have not succeeded in predicting what will happen to space when black holes collide. The reason, Thorne explains, is that Einstein's equations are "horrendously nonlinear," and so the dynamics of the collision may be very sensitive to such parameters as the masses of the black holes and the speed of their rotation and their orbit.

Thorne looks forward to the days when experimentalists record the gravitational waves from such black hole collisions and when theorists learn to simulate the events using supercomputers. "By comparing the observations with the computations, we may get a far, far deeper understanding of what gravity is all about," he says.

It is even remotely possible that researchers will eventually be able to detect the gravitational radiation from the birth of the universe, or what is called the big bang. Actually, theorists calculate that gravitational radiation was first produced about a millionth of a quintillionth of a quintillionth of a second after the big bang. They think the gravitational waves from that moment have traveled freely through the universe—without being absorbed or scattered by matter. The waves could therefore reveal what the universe was like at literally the beginning of time.

By comparison, electromagnetic radiation began propagating freely through the universe a million years after the big bang. Physicists have detected that radiation, and the discovery has led to important insights into the evolution of the universe.

Although theorists suggest that gravitational waves will emerge from spiraling neutron stars, exploding massive stars, colliding black holes and even the big bang, all their predictions are limited in a fundamental sense. They are based on information about the universe that astronomers have garnered from electromagnetic signals. Some predictions about gravitational-wave sources are almost certain to be wrong. To envision gravitational-wave sources by studying only electromagnetic radiation is somewhat like trying to guess the sound of an orchestra by watching its conductor.

Theorists also concede it is illogical to think all strong sources of gravitational radiation will emit enough electromagnetic radiation to be visible. The universe is very likely to contain sources that no one has anticipated. "The only thing that we can promise are coalescing neutron star binaries," Vogt declares. "I personally believe there is a hell of a lot more to see than that."

Vogt, now 62, has no illusions about his role. "I will be there just for the opening of the window. I will take one peek, and I will drop dead," he says with frightening conviction. "Others will learn things that I have never dreamed of and which I will never know about." But, he adds: "The first glimpse will be worth it—it justifies devoting the rest of my life to LIGO."

FURTHER READING

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