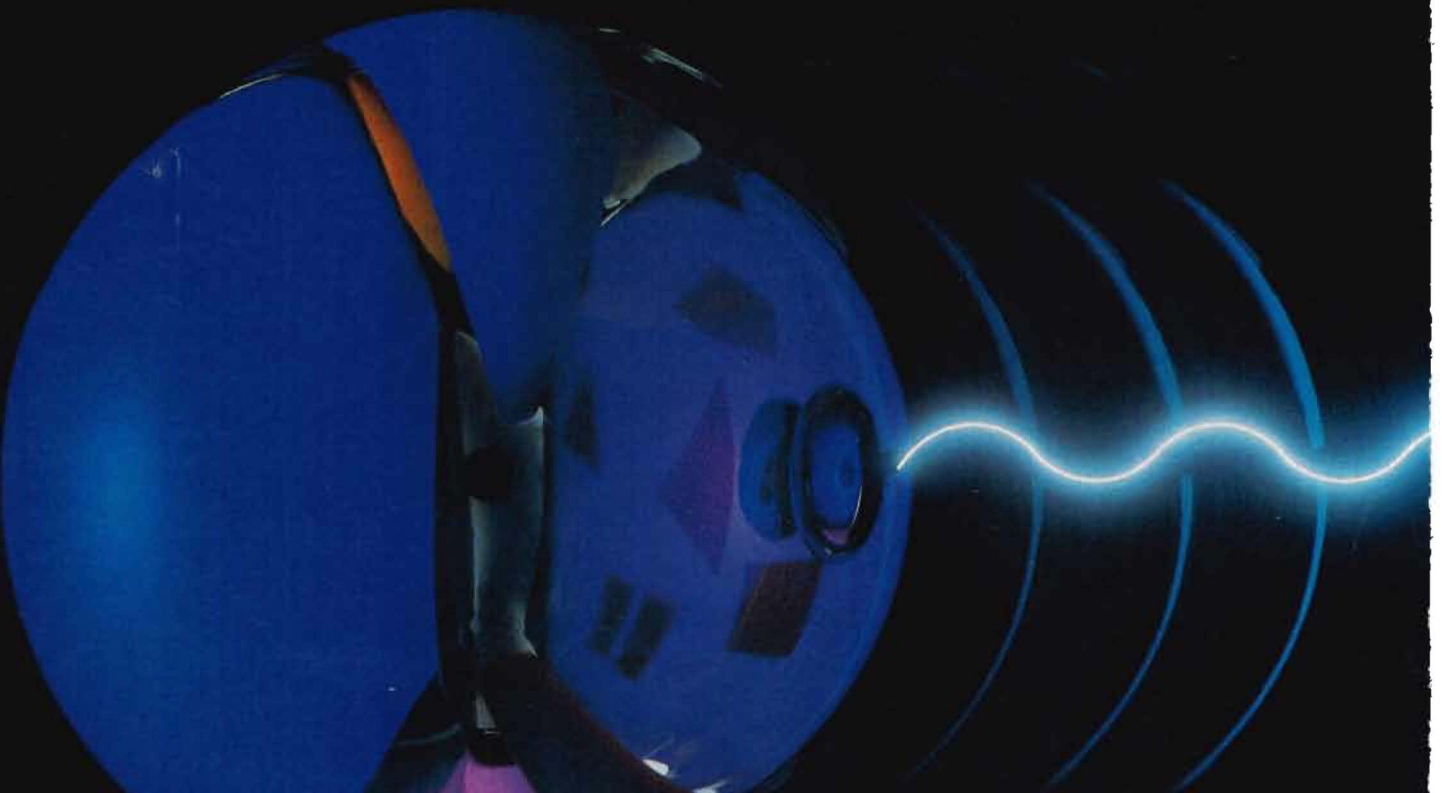
EINSTEIN'S UNFINISHED SYMPHONY



Einstein said that gravity waves exist; most modern physicists agree. The only problem is, no one's ever found one.

BY MARCIA BARTUSIAK

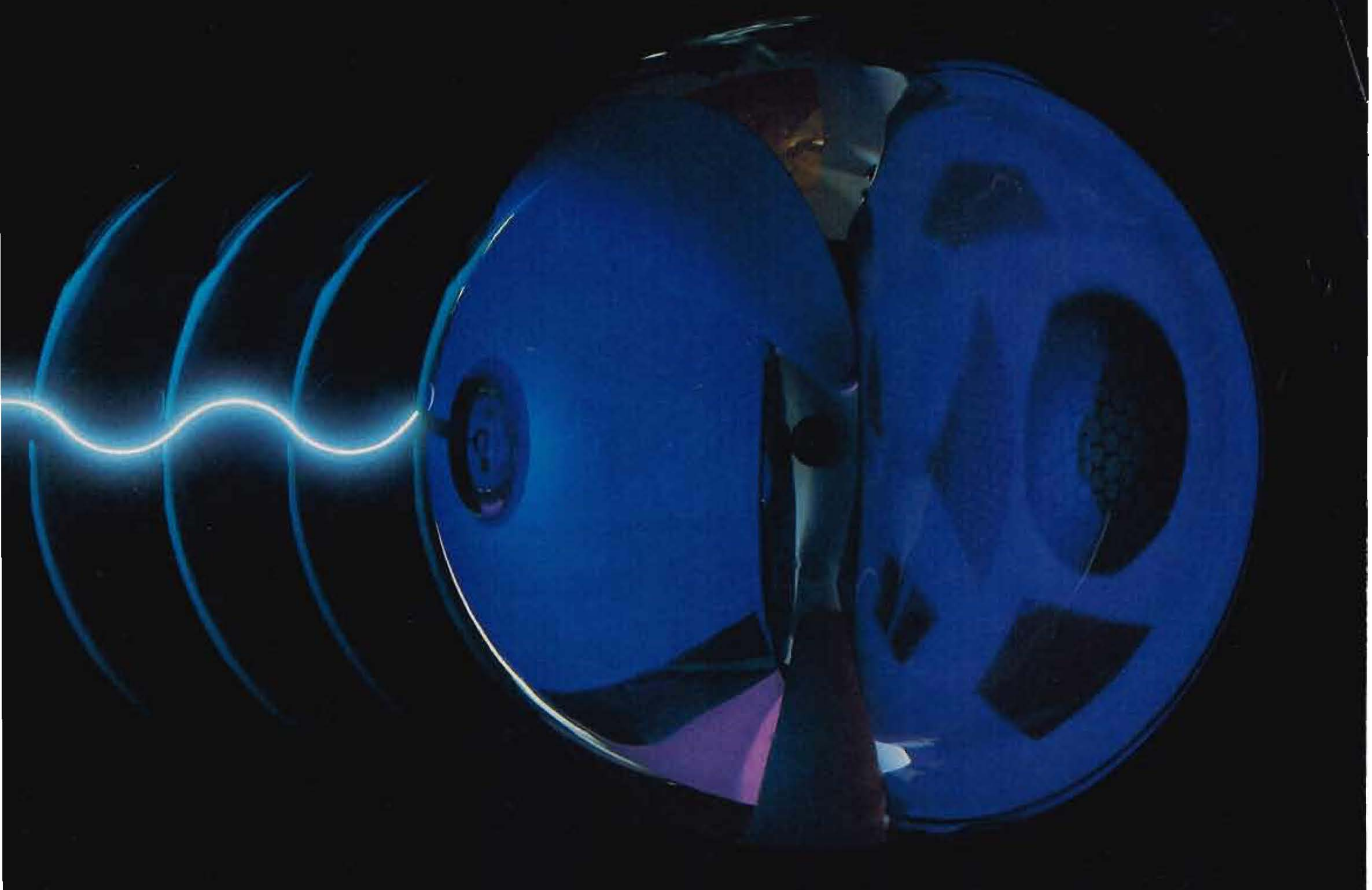
More than 160,000 years ago, at a time when woolly mammoths were first walking the Asian plains, the brilliant blue-white star Sanduleak −69°202 exploded in the Large Magellanic Cloud, a prominent landmark in the southern sky. Not until two and a half years ago, in the winter of 1987, did a wave of particles and electromagnetic radiation shot from that star reach the shores of Earth. And when it arrived, an arsenal of telescopes around the world peered in the direction of Sanduleak to observe the flickers of light and energy that represented the star's long-ago death throes. It was the first time in the history of the telescope that astronomers had observed a supernova's explosion.

When Sanduleak blew, theory suggests it also sent out waves of gravitational energy that would have generated a sort of spacequake as they rippled through the cosmos at the speed of light. A fraction of a second before the detonation, the core of the star had been compressed into a compact ball only a dozen miles wide, an incredibly dense mass in which a thimbleful of matter weighed up to 500 million tons. Jolted by such a colossal collapse, space itself was likely shaken. The resulting ripples would have rushed from the dying star as if a giant cosmic pebble had been dropped into a space-time pond. These gravity waves, though growing ever weaker as they spread from the stellar explosion, would have squeezed and stretched the very fabric of space itself. Upon reaching Earth they would have passed right through, compressing and expanding, ever so minutely, the planet and all the mountains, buildings, and people in their wake.

A few investigators, in both the United States and Europe, claim to have detected Sanduleak's faint rumble, but most experts are doubtful. The instruments with the greatest sensitivity, the ones with the best chances of detecting the waves, were not turned on at the time.

The next time one of these gravity waves rolls by, however, researchers may not be caught off guard. Even before the Sanduleak explosion, physicists at Caltech

PHOTOGRAPH BY DAVID A. WAGNER



and MIT, schools that are rivals by tradition, had joined forces to develop one of the most sophisticated gravity wave detectors to date. The two universities are proposing to construct a $150 million gravity wave observatory with one instrument positioned on the West Coast and an identical detector set in the East. If funded, such a facility could serve as the centerpiece of a worldwide network of detectors set up to snare physics' most elusive cosmic prize.

Gravity waves are Einstein's unfinished symphony, one of the few predictions of his theory of general relativity yet to be proved. With general relativity, this century's most illustrious physicist introduced us to a new, geometric vision of gravity. Space, Einstein taught, may be thought of not as an enormous empty expanse, but as a sort of boundless rubber sheet. Such a sheet can be manipulated in a lot of ways: it can be stretched or squeezed; it can be straightened or bent; it can even be indented in spots.

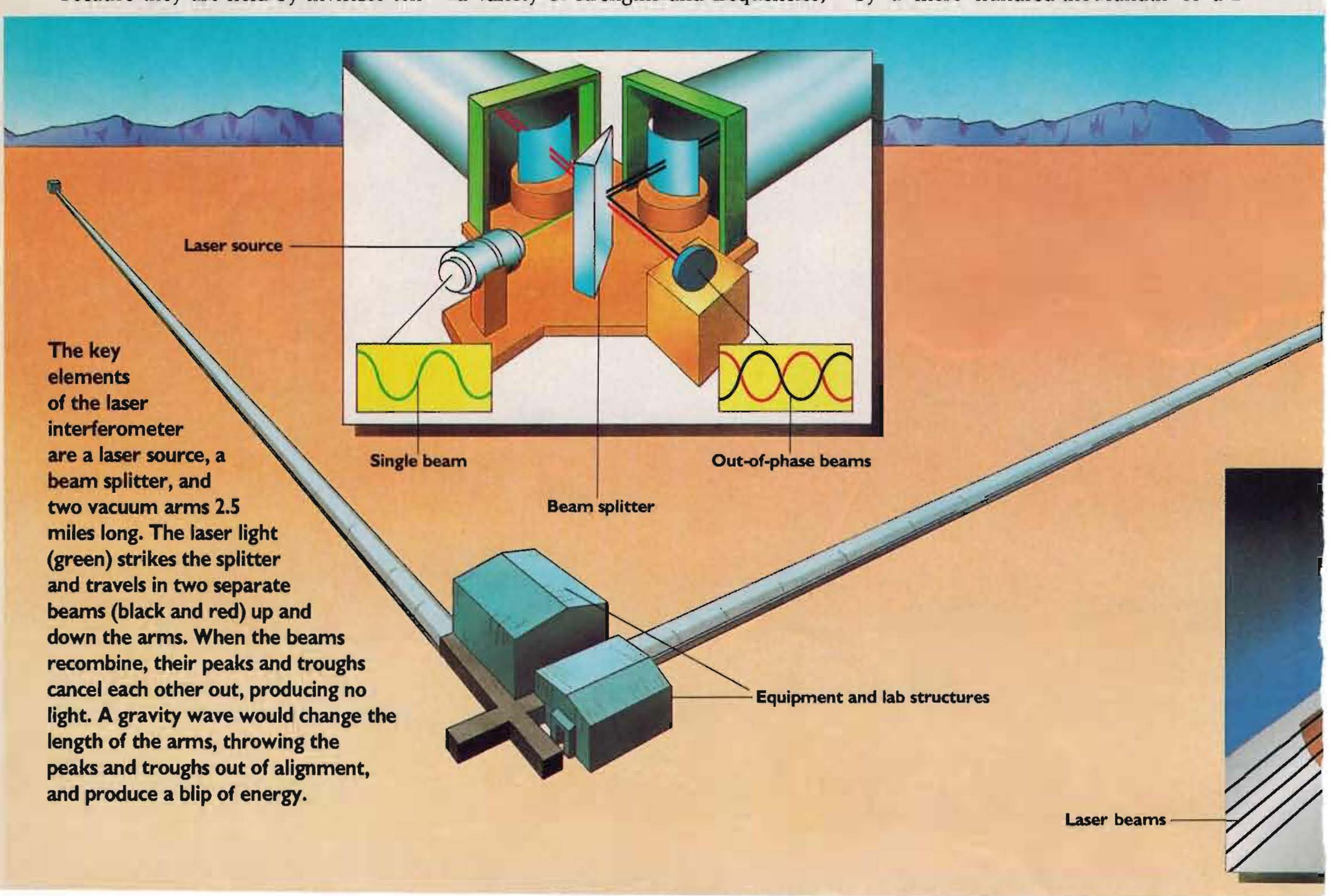
Massive stars like our sun sit in this flexible mat, creating deep depressions. Planets then circle the sun, not because they are held by invisible tendrils of force, as Newton had us think, but because they are simply caught in the natural hollow carved out by the star. As long as a heavenly body continues to exist, the indentations it creates in the mat will be part of the permanent landscape of the cosmos. What we think of as gravity—the tendency of two objects to be drawn toward each other—is a result of these indentations.

With this concept in mind, Einstein realized that space can also be disturbed. Jiggle a mass to and fro and it should send out ripples of gravitational energy, akin to the way a ball bounced on a trampoline sends vibrations across the canvas. These gravity waves would radiate outward like light waves, striking planets, stars, and other cosmic objects. But while electromagnetic waves move through space, gravity waves would be undulations in space itself. They would expand and contract the heavenly bodies they encountered and all the space around them.

Anything in the universe that has mass is capable of sending out gravity waves—in most cases all it has to do is move. Like light and sound waves, gravity waves are expected to come in a variety of strengths and frequencies, depending on the mass of the moving body and the nature of its movement. A mammoth body like a star has a powerful gravitational pull, but since it remains essentially stationary, it emits few waves. Earth, on the other hand, continually emits weak gravitational energy as it orbits the sun; the moon sends out weaker waves still as it moves around Earth. Even hopscotch players emit a gravity wave or two as they jump up and down. Waves appreciable enough to be detected, however, will emanate from the most violent events the universe has to offer: stars crashing into one another, the explosion of supernovas, the formation of black holes.

Because gravitational energy moving through space disperses and grows weaker in the same way starlight does, Einstein himself doubted that gravity waves would ever be observed. By the time gravity waves from distant stars strike Earth, they are little more than a flutter. Were a gravity wave from a supernova in the center of the Milky Way to hit this page, it would be so weak that it would change the sheet's dimensions by a mere hundred-thousandth of a

ILLUSTRATION BY ANDREW CHRISTIE

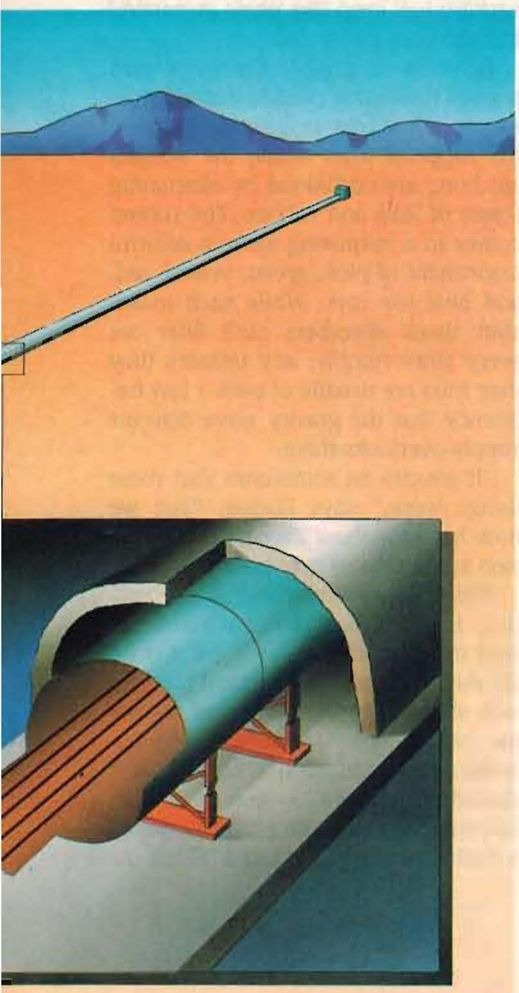


The key elements of the laser interferometer are a laser source, a beam splitter, and two vacuum arms 2.5 miles long. The laser light (green) strikes the splitter and travels in two separate beams (black and red) up and down the arms. When the beams recombine, their peaks and troughs cancel each other out, producing no light. A gravity wave would change the length of the arms, throwing the peaks and troughs out of alignment, and produce a blip of energy.

trillionth of a centimeter—a measure 10,000 times smaller than the size of an atomic nucleus.

Nevertheless, few people seriously doubt that gravity waves exist. Einstein had established three tests for his theory of general relativity. The first was that it account for a discrepancy in Mercury's orbit. Astronomers had long observed that Mercury's elliptical orbit is not entirely stable; rather the ends of the ellipse advance slightly each time the planet passes around the sun. Einstein showed that this could be explained by the planet subtly shifting its trajectory as it moves through the giant gravity well stamped out by the sun, and his calculations accurately predicted the elliptical advance.

Einstein also said that starlight passing by the sun should be seen to bend as it follows the curve of the same gravity pit, twice the bending predicted by Newton's theory. Additionally, Einstein announced that light beams flashed upward from Earth should shift toward the red end of the visible spectrum as the same gravitational effects stretched the light waves on their flight away from the planet. Both these predictions have been tested and verified by a host of researchers.



If a gravity wave from the center of the Milky Way hit this page, it could change the sheet's size by only one hundred-thousandth of a trillionth of a centimeter.

With all this evidence amassed in favor of Einstein's view of gravity, physicists are assured that gravity waves, a natural consequence of the theory, are whisking through the universe. Moreover, indirect evidence of their existence has been uncovered.

In 1974 astronomers found two neutron stars in our own galaxy rapidly orbiting each other, and they noticed that the two stars are drawing closer and closer together. The rate of their orbital decay—about one yard per year—is just the change expected if this binary pair is losing its energy in the form of gravity waves radiated into space. "This is powerful evidence that gravity waves are real," says MIT physicist Ranier Weiss. But final confirmation awaits direct detection of the waves themselves.

The honor of being the first researcher to try to snag a gravity wave goes to physicist Joseph Weber of the University of Maryland. In the 1960s Weber came up with a clever technological trick for trapping a gravity wave. He surmised that a burst of gravitational energy moving through a solid cylinder would squeeze it, ever so slightly, like an accordion. Long after the wave passed through, the bar would continue to "ring." The phenomenon is similar to the vibrations that can be produced in a tuning fork when it is struck by sound waves. In both cases the dimensions and materials of the bar or the fork determine which frequency of wave will trigger the ringing.

Weber reasoned that he could position electronic devices on either the sides or ends of the cylinder and convert the extremely tiny gravity wave induced movements into electric signals that would then be recorded and scrutinized. And in 1969 he galvanized the physics community with the announcement that he had used such a system to detect pulses emanating from the center of the galaxy. The response was not unlike this year's rush to test the claimed discovery of cold fusion. Many researchers built hardware of their own and attempted to detect the waves themselves. And although most declared they saw nothing, a fledgling branch of astronomy was born.

In the two decades since, bars of varying designs and materials have been constructed in labs around the globe. The best are cooled with streams of liquid helium to temperatures near absolute zero, in order to cut down on the thermal noises generated when atoms in the bar jostle about. At Stanford, a five-ton aluminum bar, ten feet long and three feet wide, can detect a quiver as tiny as 10^{-16} inch.

But bars have a number of shortcomings. As their sensitivities are increased, electronic noises in the detection equipment may ultimately overwhelm any gravity wave signal. At the same time, the supercooling can be tricky; if something goes wrong, it can take several months to warm up the detector, fix it, and cool it back down again. And since manufacturing and logistical limitations prevent bars from being made much larger than the one at Stanford, they can't pick up all possible gravity wave frequencies.

For these reasons a number of researchers consider an instrument known as a laser interferometer much more attractive in their quest to catch a wave. "Bars certainly have a role, and they may yet see the first sources," says Caltech physicist Michael Zucker, who has worked on bar systems himself. "But I believe laser interferometers have the flexibility to do the long-term astronomy."

Using a laser interferometer to detect a gravity wave was proposed in the late 1960s by Weiss, who first thought of the idea as a means of explaining gravity waves to his students. Weiss asked them to envision three weights suspended above the ground in an L shape. He knew that as gravity waves moved through matter or space, they wouldn't simply compress everything in their path and then, as they passed, expand it again. Rather, the waves would compress space in one direction—say north-south—while simultaneously expanding it in the other—say east-west.

The phenomenon is akin to the squeezing of a balloon: press in on the balloon's sides and the rubber will immediately bulge out from its top and bottom, in a direction perpendicular to the squeeze. Likewise, if a gravity wave were to come flat down on an interferometer's L, a right angle, the masses in one arm would squeeze closer together while the masses in the other would expand farther apart. A millisecond later, as the wave continued onward, this effect would reverse, with the compressed arm expanding and the expanded arm contracting. Weiss concluded that laser beams could detect and monitor those flutters.

He imagined a continuous stream of light from a laser entering the corner of the system and being split into two beams, each directed down an arm of the L. Mirrors affixed to the center and end masses would then bounce this light back and forth many times. If a gravity wave caused the masses to move, the two laser beams would travel slightly different distances, and the repeated ricochet would magnify the difference enough for sensors to detect. The further apart the masses were placed, the better the system would operate.

Throughout the 1970s researchers at other labs began building and testing laser systems of their own. One of these designers was Scottish physicist Ronald Drever at the University of Glasgow. In his hands, the science of laser interferometry blossomed, especially when he invented a new way of stabilizing a laser beam: keeping the wavelength of a laser's light pure and steady, long a technical obstacle, was crucial if gravity wave astronomers ever hoped to monitor infinitesimal quivers in their masses. Drever also devised a type of interferometer that required smaller mirrors, an expensive item at the time. "In Scotland we needed to do things on the cheap," he jokes.

MIT's interferometer has arms barely five feet long, lilliputian compared with a proposed 2.5-mile-long system.

By 1979 Drever was asked to join the "big leagues," as he affectionately calls Caltech. He made the move, lured by its promise of greater financial support and better equipment. Caltech's Kip Thorne, a world-renowned expert on general relativity, had convinced university administrators to allocate $500,000 to establish a gravity wave astronomy program at the school. With Drever's help the school intended to build a sophisticated interferometer prototype, the largest in the world. This would allow Caltech to refine the hardware and techniques necessary for a full-time gravity wave search.

Today the gravity laboratory set up by Drever and his colleagues looks almost like an afterthought on the northeast corner of the Caltech campus. The one-story structure, with its beige steel-shingle siding, wraps around a corner of the university's engineering shop, forming two long corridors. Only an unassuming sign by the door, simply marked GRAVITATIONAL PHYSICS, reveals the building's purpose.

Inside, the lab's most prominent features are two eight-inch wide, 130-foot-long steel pipes hung from supports and meeting at right angles. At the three corners of the L are big glass bell jars, in which the test masses are suspended. Each mass is a three-pound cylinder of fused silica. When first built, the glass tanks were christened Huey, Dewey, and Louie, after Donald Duck's nephews—a tip of the hat to nearby Disneyland. Inside the long pipes, the laser beams flash, reflecting back and forth from Huey to Dewey and from Dewey to Louie. Vacuum pumps rhythmically chugging in the background keep the pipes evacuated and the laser paths clear.

In order to protect the suspended masses from such outside disturbances as passing trucks or seismic tremors, the supports from which the weights are hung are cushioned by alternating layers of lead and rubber. The rubber comes in a surprising form: a colorful assortment of pink, green, yellow, red, and blue toy cars. While such makeshift shock absorbers can't filter out every stray rumble, any tremors they may miss are usually of such a low frequency that the gravity wave detector simply overlooks them.

"It amazes us sometimes that these things work," says Zucker. "But we now have the most successful suspension system we've ever had."

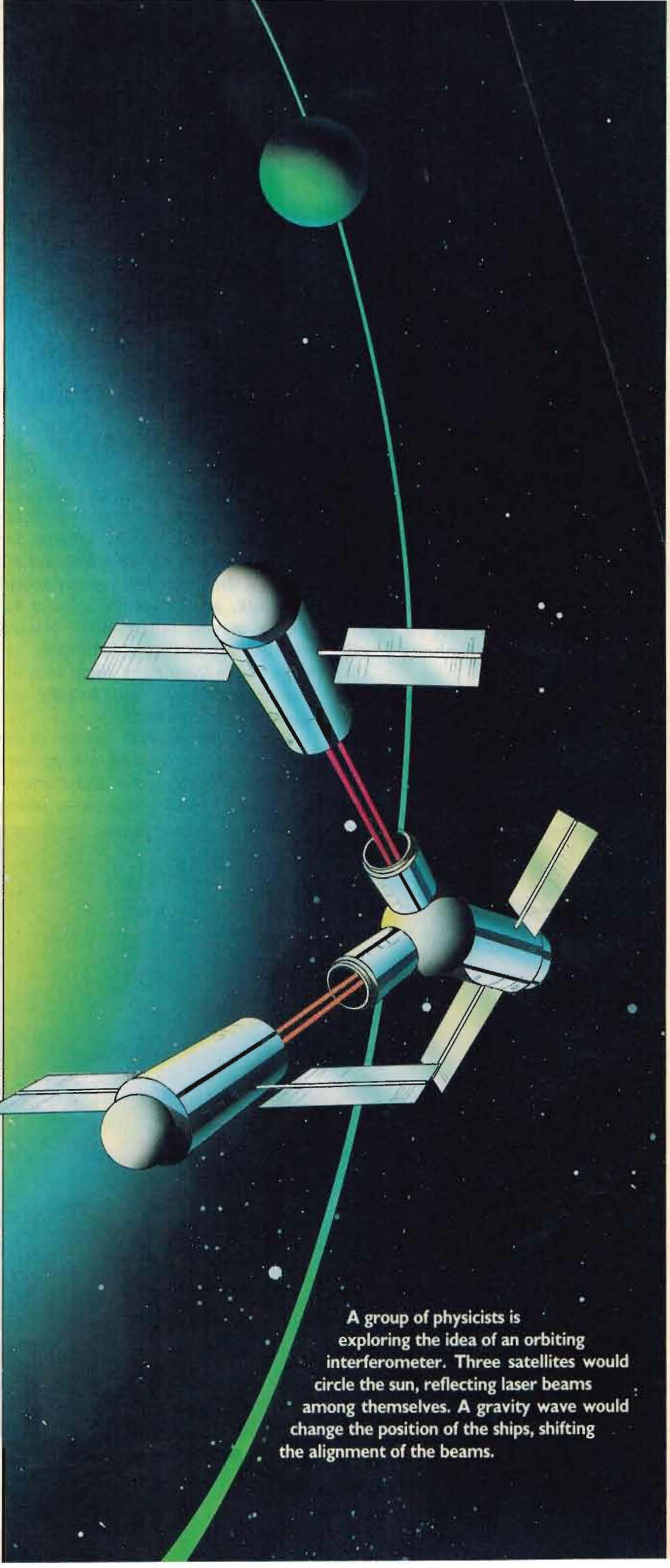
When the interferometer is in operation, the laser beams in each arm are kept out of sync with each other, with all the peaks of one beam lining up with all the troughs of the other, so that the beams, upon recombining (or interfering), cancel each other out. If a disturbance, like a gravity wave, knocks the beams into phase, however, a flash of light is produced. What the researchers are looking for, ideally, is a tiny blip on the computer record that would indicate a wave has gone by.

Five years ago the Caltech detector could sense movements of less than a trillionth of an inch in the masses. Today it can detect shivers a thousand times smaller. The progress was largely due to a series of technological improvements such as "supermirrors" made of layers of dielectric material that lose only 100 photons for every million reflected. Switching to more powerful lasers will increase interferometer sensitivities even more.

As with all laser-based systems at this stage, the Caltech interferometer is less a true gravity wave telescope than a working model. It still needs a tenfold improvement in power to match the Stanford bar. However, for 12 days and nights in the winter of 1983 the interferometer was hastily put on the air after radio astronomers discovered a neutron star spinning a record 642 revolutions per second. The 1987 Magellanic supernova was examined, too, though days after the initial burst. In both cases the Caltech detector perceived not a jiggle.

An important step in developing interferometers that can do some real detecting came in 1983 when Weiss, at MIT, completed a feasibility study for a pair of mammoth interferometers with arms up to 2.5 miles long. The two units would be built at sites at least 600 miles apart. This remote spacing would help investigators verify that any rumbles they might detect were not ground tremors or other local events, but authentic gravity waves. Building such a system would not come cheap; Weiss's estimates put the cost in the tens of millions of dollars.

Caltech too dreamed of a miles-long interferometer. The jump in sensitivity from the on-campus prototype to such a sprawling system would be comparable to the difference between the human eye and a 200-inch telescope. Knowing the government wouldn't fund both schools' programs, Caltech soon joined forces with MIT to work together on a single pair of giant interferometers. They recently dubbed their project LIGO, for laser interferometer gravitational wave observatory.



A group of physicists is exploring the idea of an orbiting interferometer. Three satellites would circle the sun, reflecting laser beams among themselves. A gravity wave would change the position of the ships, shifting the alignment of the beams.

ILLUSTRATION BY ANDREW CHRISTIE

Within the physics community, support for the project was at first lukewarm; but attitudes changed in 1986 when a committee convened by the National Science Foundation concluded that such a facility "will ultimately provide for a giant leap in our understanding of the gravitational force." Last fall the National Science Foundation signaled its support with a $10.6 million grant to help Caltech-MIT collaborators draw up further designs. Additional funding still hinges on approval of a final proposal.

In a labyrinthine Caltech basement, the project's progress is measured by the growing number of blueprints now filling the bulletin boards. The western site for the proposed observatory has already been chosen: the far northeast corner of Edwards Air Force Base in California's Mojave Desert, near the dry lake bed used for shuttle landings. The search is now on for an eastern site, with Maine and Louisiana among the leading candidates.

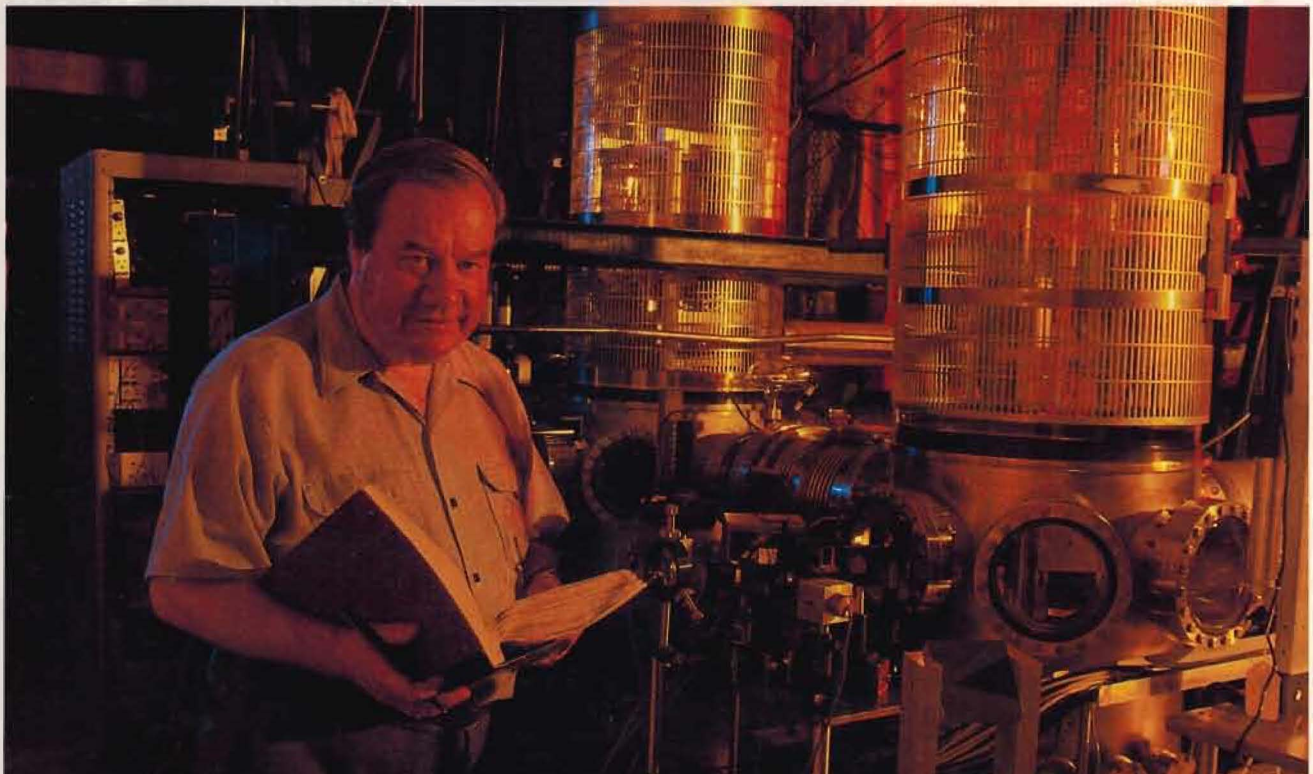
The interferometers' arms would be stainless steel conduits four feet in diameter, roomy enough to accommodate up to six laser beams linked to six sets of masses; each silica mass would weigh anywhere from a few pounds to a ton. The use of different masses allows the astronomers to tune each interferometer like a radio, hunting for gravity waves of different frequencies. Some of the lasers will operate round the clock, always on the lookout for gravity waves; others will be used mostly for tinkering, allowing researchers to learn more about interferometer technology and steadily upgrade their equipment.

The observatory is "semiguaranteed" to detect the crash of two neutron stars, paired in a binary system, spiraling into each other as their orbital dance decays.

Surprisingly, up to 80 percent of the cost of the project will not go into sophisticated computers and electronics, but into constructing pipes, laying mortar, and building vacuum pumps—the low-tech elements of this high-tech construction job. Perhaps the toughest engineering challenge the group faces is how to draw all the air out of the 2.5-mile arms, a necessary step if the laser beams are to travel up and down without wavering or shimmering.

"Essentially, what we're trying to do is dig large holes in the atmosphere," says vacuum expert Boude Moore. The engineers are setting their sights on an evacuation that is nearly one-hundredth of a billionth that of sea-level pressure—not a record, but a formidable feat nonetheless.

To help accomplish this, Moore is testing a type of steel with an extremely low hydrogen content. Ordinarily, hydrogen atoms leak out of steel, and this can clog up a vacuum. Designers of particle accelerators deal with this problem by heating their pipes before using them; this excites the hydrogen molecules and coaxes them out of the metal, where they can simply be vacuumed away. By limiting the hydrogen from the start, however, engineers won't have to spend $5 million heating miles of pipe. "People say we're nuts to try it," says chief engineer William Althouse. "But



Gravity wave investigator Ronald Drever stands next to the central masses of Caltech's laser interferometer.

vacuum technology is a black art." If approved by 1990, the twin detectors could be up and running by the middle of the decade. The system's scheduled lifetime is 20 years.

One phenomenon that Thorne believes the observatory is "semiguaranteed" to detect is the resounding crash that occurs when two neutron stars, paired together in a binary system, spiral into each other as their orbital dance decays. The one known pair that exists in the Milky Way orbit each other about every eight hours. The final collision of the two balls of compact matter won't occur for several hundred million years, but as soon as the gravity wave detector is sensitive enough to see beyond the Milky Way, it may pick up binary neutron-star bursts in other galaxies, possibly several events a year.

If signals from such stars are detected, they could be a boon to cosmologists, who have long been arguing over the universe's size. Current measurements of distance rely on such yardsticks as the luminosity of stars and the apparent size of galaxies, but astronomers quibble about how to interpret what they observe. As a result, estimates of distance can vary by factors of two, and that's as vexing to astronomers as if geographers could only estimate the distance between New York and Los Angeles as somewhere between 2,000 and 4,000 miles. But by knowing the amount of gravitational energy emitted by colliding neutron star pairs and comparing these estimates with the strength of the waves when they arrive on Earth, astronomers could calculate how far the waves had to travel to reach our planet. This, in turn, could provide a sort of measuring tape to the galaxies.

The sighting of a supernova is also a possibility, although astronomers say this is not assured; a lot will depend on the explosion's messiness. If the collapse of the remnant core is perfectly smooth and symmetrical, gravity wave astronomers will not hear even a whimper; gravity waves emitted symmetrically tend to cancel each other out much the way that out-of-phase light waves do. At the same time that one part of the wave is causing space to expand, another part is causing it to contract; the net result is no change at all. But if the explosion is uneven or

PHOTOGRAPHS BY JEAN-MARC GIBOUX/GAMMA LIAISON

Caltech's remarkable interferometer has some unremarkable components: tiny rubber cars help cushion the system's suspended masses against tremors.

lumpy, as most are, a signal with waves stretching hundreds of miles from peak to peak will be sent out.

Dramatic as such supernova waves would be, Thorne's most hoped-for sighting is the collision of two black holes, objects so dense that no bit of light or matter can escape their powerful gravitational grip. "If I had to lay bets on how we'll finally get one hundred percent proof that black holes exist," he says, "it would be that."

Astronomers already suspect that black holes are circling distant stars; but the evidence is circumstantial. X-ray telescopes frequently pick up signals from remote orbiting bodies, yet when astronomers peer through optical telescopes, they see nothing. But if two black holes should be orbiting each other, they would eventually spiral in, releasing an unmistakable set of gravitational waves. "They would give themselves away right off," declares Thorne: first, an ever higher whine during the final minute of the fateful twirl, then a cymballike crash as the holes coalesced, and finally a ring-down as the merged holes settled together.

Elsewhere in the heavens there could be a bevy of other types of gravity wave emitters. A neutron star with a bump on its surface—an inch-high mountain, for instance—would continually transmit gravity waves as the bulge rotated with the star. Cosmic strings, thin tendrils of primordial energy left over from the universe's birth, may also send out waves as they decay.

To catch these even lower-pitched gravity waves—possibly even the ancient echo of the Big Bang—optimistic designers are already considering going a step beyond the Caltech-MIT system. Researchers at the Joint Institute for Laboratory Astrophysics in Boulder are designing an orbiting interferometer: three spacecraft would circle the sun in formation, and laser beams would monitor any change in distance between the units.

Meanwhile, on the ground, gravity wave researchers in West Germany, Scotland, and Japan have their own interferometer prototypes. Scientists in Italy, France, and Australia are also exploring the field. All these systems could one day join the Caltech-MIT observatory in a global network, working together to verify any wave detection and pinpoint the sources.

Yet not everyone in the astronomy community is enthusiastic about the project. Bar-detector scientists like to point out that bars are cheaper than laser interferometers. Other critics question the importance of gravity wave studies altogether, insisting that scarce government funds could be better spent on projects with lower price tags and far likelier scientific payoffs.

Final backing by the National Science Foundation may depend on whether administrators will be placing their limited funds on scientific sure bets or on relative long shots. Rochus Vogt, director of the Caltech-MIT collaboration, says it's not a total gamble.

"With this detector we can guarantee a minimum return," he pledges. "We can promise stars collapsing and exploding into supernovas. We can promise colliding binary neutron-star systems. Of course," he adds, "what will be more exciting than all those things we can predict will be those things we can't." ❑

Marcia Bartusiak wrote about dark matter in the December issue.