SENSING THE RIPPLES IN SPACE-TIME

Astronomers have watched the universe with light, radio waves, and x rays. Now they're trying to open a new window—gravity waves.

BY MARCIA BARTUSIAK

PHOTOGRAPHS BY RENE SHERET
DRAWINGS BY JEAN WISENBAUGH

SOME CALL IT A TELESCOPE. But it's surely the oddest looking telescope on Earth. No mirrors or lenses are aimed toward the heavens, ready to capture the light waves racing toward us from far-off galaxies. Instead, there is a hulking metal tank—a sophisticated thermos bottle, actually—that encloses a five-ton aluminum bar cooled with streams of liquid helium to a chilly -456 degrees Fahrenheit.

And this glacial mass of instrumentation doesn't sit on high mountains. It resides in the very heart of Stanford University's pastoral, red-tile-roofed campus in California, in what looks like a deserted aircraft hangar, at the end of a narrow, winding, concrete tunnel that was once part of the original Stanford Linear Accelerator Laboratory. Particle physicists used this cavernous end station to unlock the secrets of the atom. Today, Stanford scientists are here with their supercooled detector to snare a quarry that has ever eluded celestial observers: gravitational waves, a means of observing the universe's most enigmatic—and violent—goings-on.

Albert Einstein first predicted the existence of these unusual waves almost 70 years ago. It was a natural outcome of his famous theory of general relativity, which taught us to view gravity not as a mysterious force but rather as a curvature in space-time. Space, Einstein was telling us, is like a boundless rubber sheet, and large masses, such as our sun, indent this flexible mat, causing any passing rocket, planet, or light beam to just follow the natural depression. Celestial bystanders perceive it as an attraction to the sun and call it gravity.

Yet this century's most illustrious physicist also realized there would be peculiar side effects to this strange new geometric picture. Einstein's equations revealed that if a mass were suddenly accelerated or jostled to and fro, it would generate ripples in that sheet of space-time, similar to the way electrons moving along an antenna generate radio waves in the air. But while such electromagnetic waves travel *through* space, gravity waves

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actually disturb the fabric of space. This space-time rippling occurs every time you bang your fist on a table or jump rope, but only the most awesome cosmic events emit any appreciable waves. Particles and planets caught in the path of such a wave would experience space itself contracting and expanding.

Such a "spacequake" would provide astronomers with an entirely new form of information about the universe. "Visible and infrared light, radio waves, and x rays are emitted almost entirely by individual atoms, molecules, and high-energy particles," explains Caltech theoretical physicist Kip Thorne. "Gravitational waves, by contrast, are emitted by the bulk motions of huge amounts of matter, objects that are vibrating, collapsing, or exploding."

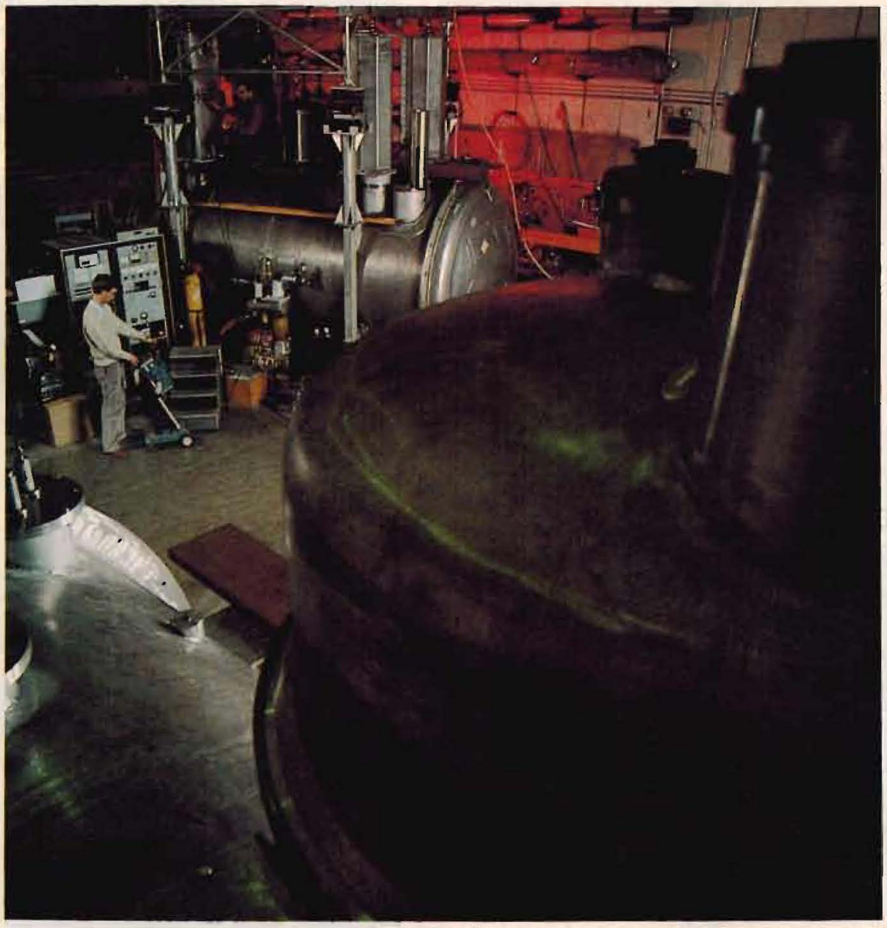
More important, these periodic distortions in the structure of space-time can blithely pass through interstellar dust, planets, and galaxies as if they weren't there. Nothing can absorb them. This penetrating power may allow astrophysicists to observe cosmic processes that, for now, can only be imagined on a computer graphics terminal—from the last millisecond gasp in the life of a star to the titanic collision of two black holes.

It's an intriguing, even frightening prospect but, in Einstein's day, hardly of much consequence. He was sure they would never be seen, and with good reason: Imagine that an aged star has just died somewhere in the center of our Milky Way, spectacularly exploding as a brilliant supernova. "It's one of the most dramatic events that can happen in the universe," says physicist William Fairbank, head of the Stanford gravity wave project. "In less than a dozen seconds, the core of that star will collapse from the size of our Earth to the size of the Stanford campus." Under such conditions, matter gets so compressed that protons and electrons merge to become a solid ball of neutrons (hence the tag, neutron star).

The collapse is so sudden that the star's gravitational field also undergoes a rapid transformation, and this change is transmitted toward Earth at the speed of light as a gravitational wave. But by the time that warp in space-time hits the piece of paper you are now reading, the energy will have been spread out over a vast distance. This will cause it to be so weak at any one spot that it will change the sheet's dimensions by at best only one-thousandth the diameter of a proton—an infinitesimal ten-thousandth of a trillionth of a centimeter. A wave rushing in from the Virgo cluster of galaxies, some 50 million light-years away, would be a thousand times weaker.

Such minuscule movements make gravity wave astronomy look virtually impossible. But amazingly enough, these tiny quivers in space-time now have a real chance at being recorded.

The first attempt at snaring the ghostly ripples was made in the 1960s when Joseph Weber of the University of Maryland, the acknowledged father of gravitational wave astronomy, built the first set of detectors. It was Weber who devised a nifty technological trick for trapping a wave: A gravitational wave, he surmised,



The detector that now has the best chance of registering a gravity wave is Stanford's supercooled bar. A passing gravity wave would squeeze the cylinder in and out, and the vibrations would be monitored by an electronic device at one end of the bar.

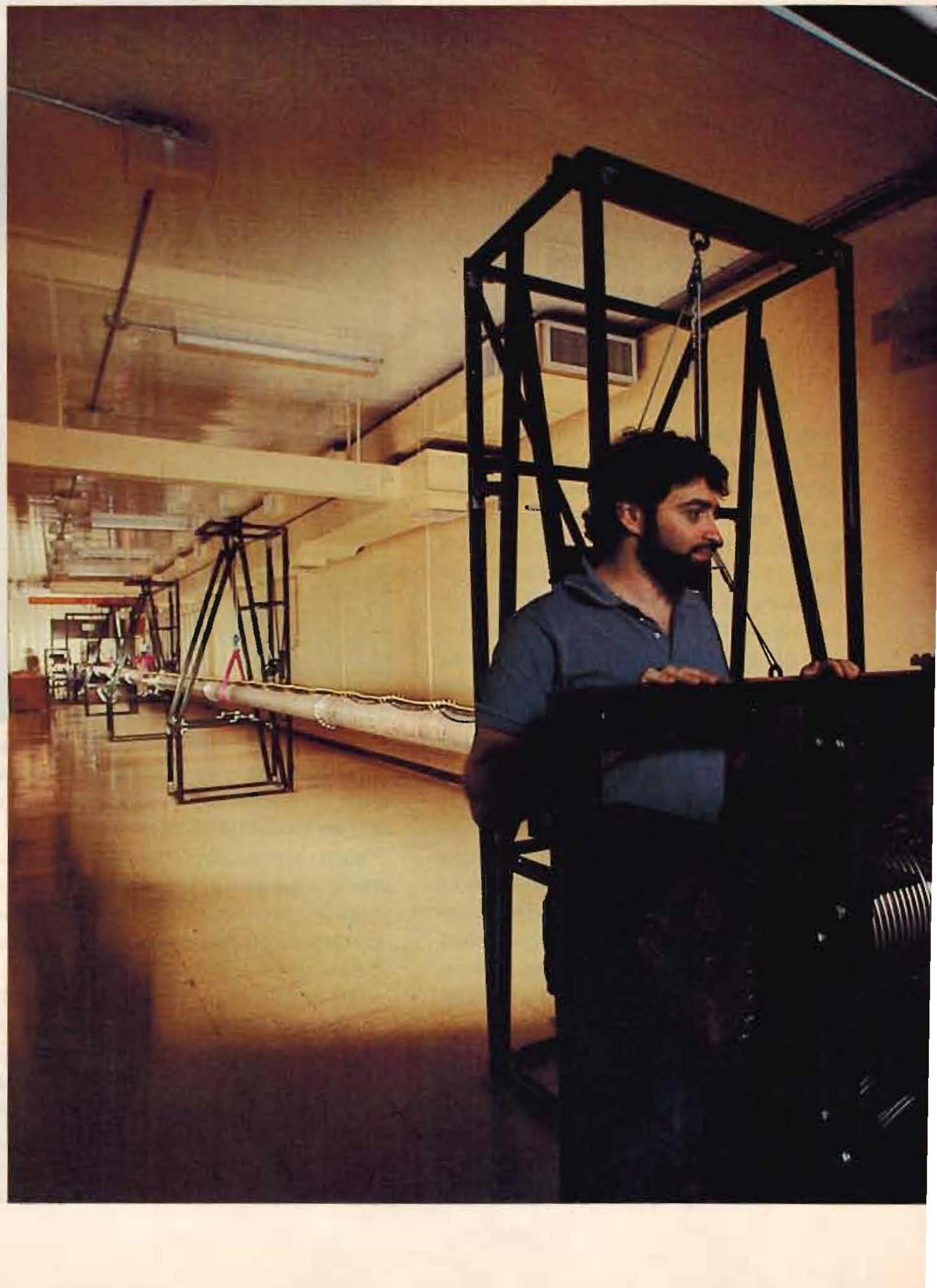
would ever so slightly squeeze a solid cylinder in and out like an accordian. But then, like a bell, the bar would continue to "ring" long after the wave passed by. This ringing would be the gravity wave's calling card.

With massive aluminum bars operating on both the Maryland campus and the Argonne National Laboratory near Chicago, Weber announced in 1969 that he had registered some pulses. Based on the direction from which the strongest signals came, these bursts appeared to originate in the center of our galaxy. Catalyzed by the announcement, several groups quickly constructed their own detectors. Excitement within the physics community, however, was short-lived. Though a few facilities have reported seeing pulses similar to Weber's, most have failed to detect the same kind of ringing. "What Weber was seeing remains interestingly unknown," says Fairbank. But Weber's relentless effort did transform a seemingly hopeless endeavor into a lush, new field of experimental physics.

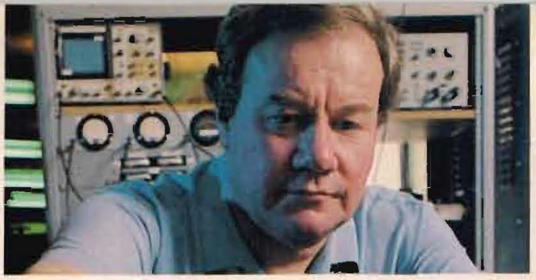
Currently, the Stanford group stands the best chance at capturing a bona fide wave. Even as Weber was constructing his first detector, Fairbank and colleague William Hamilton were designing a supercooled version. "We did this to eliminate the random noise in the bar," explains Fairbank, a world-renowned expert in low-temperature physics. "The normal motions of an atom at room temperature are 3,000 times greater than the energy put into the bar by that collapsing star at the center of our galaxy." The noise can never be eliminated entirely, but supercooling reduces these spurious signals, increasing the chances of picking up the fainter, gravity-induced movements.

In the course of the last four years, Stanford's most advanced gravitational wave antenna to date has stood in stately isolation in its windowless cavern. The rumblings of passing cars and trucks are damped by suspending the 10-foot-long, three-foot-wide metal bar with special springs. "You could actually gently hammer on the outside shield and not get a signal," says Fairbank proudly. And, as in Weber's original scheme, electronic devices positioned on the end of the bulky aluminum cylinder convert its minute movements into electrical signals that are recorded and scrutinized for a gravity wave's unique fingerprint.

Right now, the Stanford bar can sense a shiver as tiny as 0.0000000000000003 centimeter (one thirty-millionth the size of a hydrogen atom), a world's record for the field. Further improvements are being made under the direction of senior



An alternative to the bar is a detector that uses laser beams and suspended masses, arranged in an L shape. The passing of a gravity wave would be indicated by a change in the distance between the masses. Caltech's test model of this device, at right, has arms only about 130 feet long, but scientists at Caltech and MIT are building similar models with three-mile-long arms. They hope to set these larger detectors up several thousand miles apart in undisturbed locations, perhaps underground or in the desert.

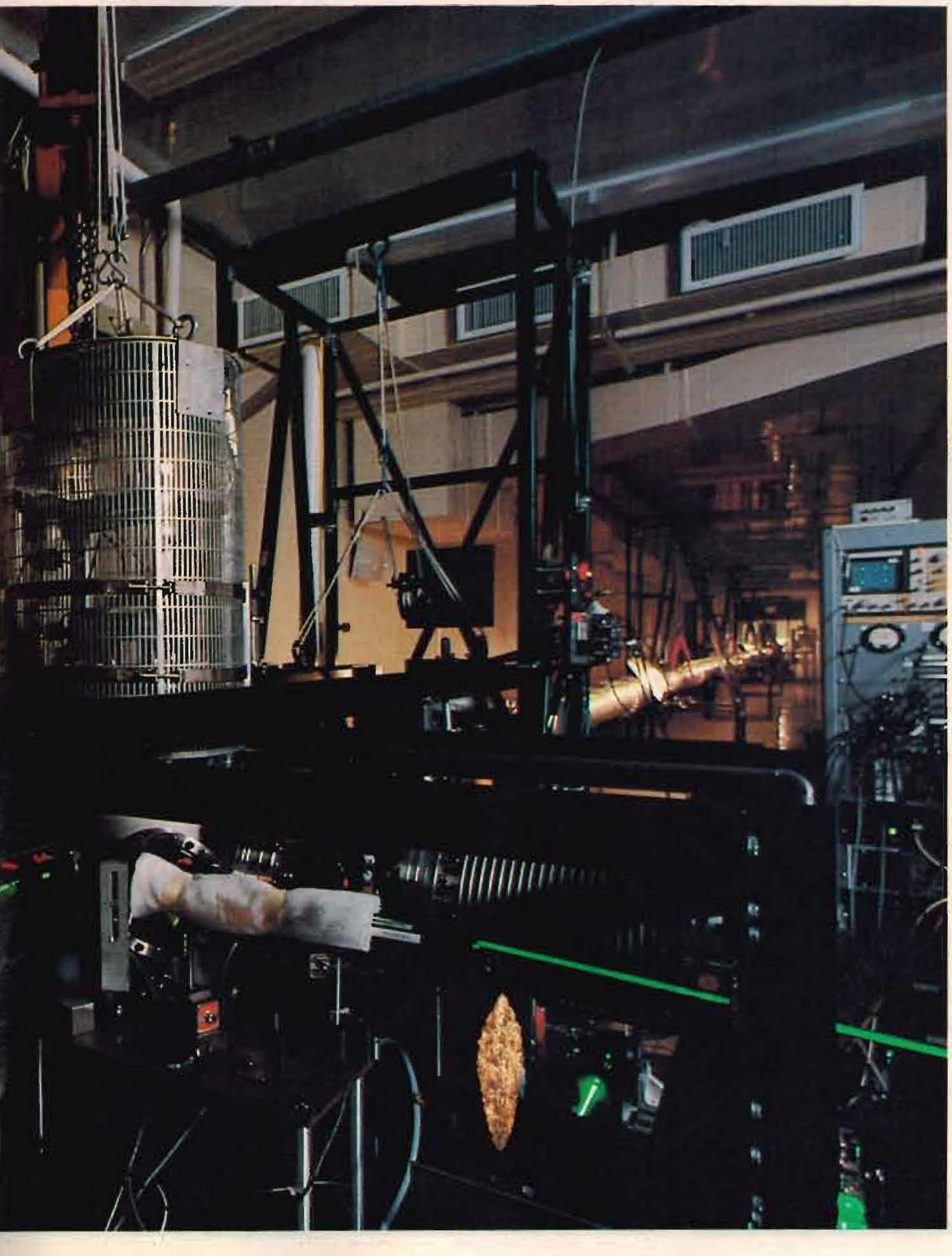


"Simultaneous signals from several detectors could herald a new era in physics and astronomy."
—Ronald W.P. Drever

research associates Michael McAshan and Peter Michelson. Their plans to install more advanced electronics and to cool the bar to within a hundredth of a degree of absolute zero are expected to increase the bar's sensitivity a hundred times.

During its last year-and-a-half run, this futuristic telescope registered a number of "events" that could not be explained away as laboratory jitter. Yet no one knows if they were gravitational waves. "With just one bar of this kind," says Fairbank, "the best you can say is, 'I saw some signals no bigger than a certain amount.'"

Scientists will only be sure of what they are seeing when additional, equally sensitive supercooled detectors come into use that can measure these disturbances simultaneously. Already, the Stanford gravity wave team is assembling a matching detector just a few dozen yards from their present instrument, and another twin is being built at Louisiana State University under the direction of Hamilton. The second Stanford detector will allow them to rule out internal instrument error when a ripple is detected, and the Louisiana detector, similarly, will rule out local glitches.



It's truly a global pursuit. Other supercooled bars of varying designs and materials (niobium, sapphire, and silicon as well as aluminum) have either been assembled or are planned at the Universities of Maryland, where Weber continues his pioneering work, Rochester, Rome, Tokyo, and Western Australia, as well as in China and the Soviet Union. Like surveying instruments, an array of detectors will enable astronomers to more precisely pinpoint the source of an incoming wave.

But watching bars of metal vibrate is not the only means of stalking these alleged ripples in space-time. More than a decade ago, researchers such as Robert L. Forward of Hughes Research Laboratories and MIT's Rainer Weiss recognized another way to catch a gravity wave: Attach mirrors to three heavy masses, suspend the masses in a vacuum some distance from one another, and monitor their relative motions with a laser beam to see if a passing gravitational wave has wiggled the weights.

Since a gravity wave acts by compressing space in one direction while expanding it in the other (see illustration next page), a popular configuration for this setup is an L shape, with a mass at each end and one at the corner. "Envision a gravity wave coming straight down on the L," suggests physicist Ronald Drever, head of Caltech's gravitational physics group. "Then the masses in one arm will draw closer together by a distance many times smaller than an atomic nucleus, while the other two get farther apart. A millisecond later, as the wave passes by, the effect will reverse."

Test models of this setup have been built in Scotland, West Germany, and at MIT, and are under development in France and Russia. But Caltech now boasts the world's largest gravity wave laser antenna. Each arm of their L stretches out for 40 meters, a little more than 131 feet. Upon entering their spanking new annex, you might think that you had stumbled upon the campus utility room. Most of the space is taken up by what looks like two long water pipes meeting at right angles. Actually, they're the evacuated pathways for the laser beams.

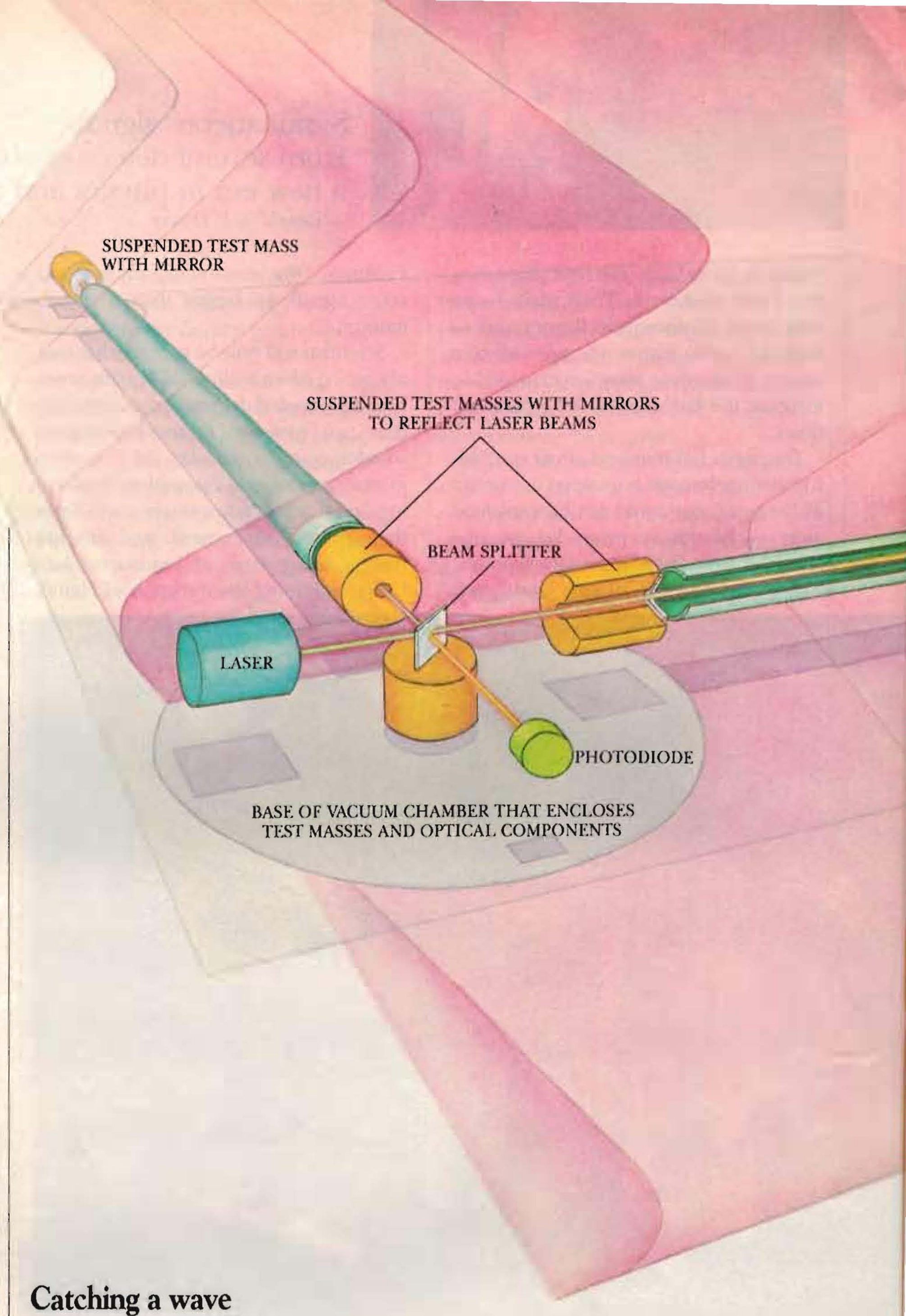
The impish ingenuity for which Caltechers are famous is readily apparent. The supports from which the 22-pound brass weights are suspended are cushioned against outside tremors by resting on alternating layers of lead and toy rubber cars—a colorful assortment of pink, green, and blue Mercedes Benzes and dune buggies. "What can I say?" asks Caltech astrophysicist Stan Whitcomb, who directed the system's construction. "They were the handiest things to buy at the time."

Operating the system is a more serious endeavor. First, a continuous beam of pure green light from an argon-ion laser enters the crook of the L and is split in two. Each half races down one of the evacuated arms and reflects off a mirror mounted on the end mass. This light bounces up and down the arm several thousand times, until eventually the two beams are directed back out of the arms and compared.

"We're looking for the slightest flicker of change in the beams," says Caltech gravity wave physicist Robert Spero. Although the two beams are constantly in step with one another as they bounce within their respective arms, the optical system is such that they are made to be out of phase when they recombine. At this point they cancel each other out and produce a patch of darkness.

But a passing gravity wave would suddenly change the arm lengths. This in turn would change the phases of the beams that emerge from the arms. In greatly simplified terms, the two beams, once recombined at the center of the L, would constructively interfere and produce a tiny burst of light. "Ideally," says Spero, "we'll start out with a flat trace on a chart recorder, and a gravity wave would show up as a blip, a spike in the smooth trace."

Though the Caltech scientists see their detector as still only a "test bed," they have conducted one serious search. For 12 days and nights in the winter of 1983,



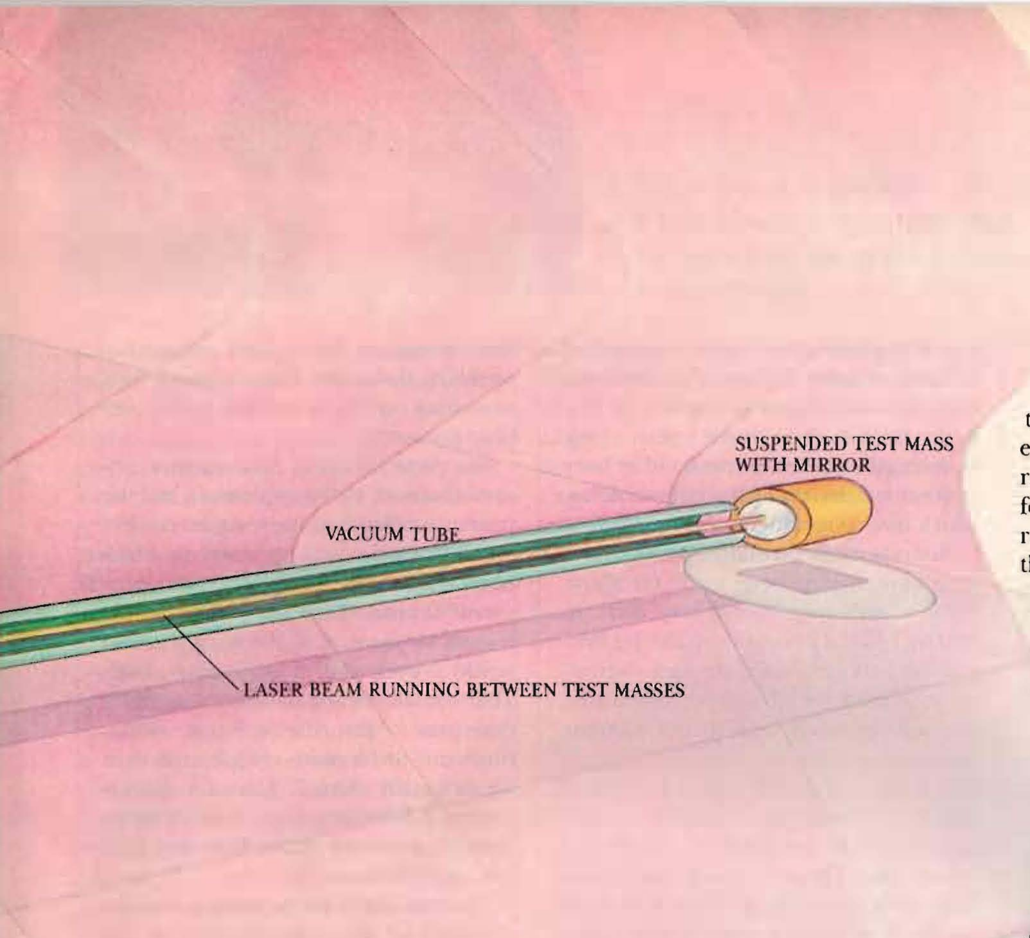
Catching a wave

The gravitational wave detector represented above is based on the assumption that a passing gravity wave, by disturbing space, will change the relative distances between suspended masses. Typically, the masses are arranged in an L, so that a gravity wave (shown in pink) traveling downward onto the detector will make the two masses of one arm move closer together, while the masses of the other arm move farther apart.

According to Ronald Drever, head of the Caltech gravitational physics group, this type of detector has the potential to pick up waves from a variety of sources in the universe. Although in the present Caltech model the masses are only about 130 feet apart, they can in principle be placed miles apart, making the detector very sensitive.

Some of these detectors use three masses, one at the end of each arm and one in the center, which holds the beam splitter. The Caltech scientists have chosen to use four test masses and attach the beam splitter and other optical components (not shown in this simplified illustration) to a separate support.

Any change in the distance between the



masses would be indicated by laser beams that continually measure the length of the arms. A laser beam enters the central vacuum chamber (the base of which is indicated in the illustration by the gray area) and passes through the beam splitter. The two halves of the beam then travel down the vacuum pipes that make up the arms of the L.

The masses at each end of the vacuum pipes are equipped with mirrors to reflect the light; each beam is made to bounce back and forth between these mirrors, following the same path repeatedly. This increases the total length of the light path so that if the masses do move, the effect is magnified. The beam can make 30 to several thousand trips before the beams are recombined in the central vacuum chamber and directed to a photodiode, which "reads" the phase difference of the two beams. This signals any movement of the masses, which could have been produced by a passing gravitational wave. A signal received more or less simultaneously at two detectors a few thousand miles apart—or even better, at several locations around the world—would be strong evidence that a gravity wave had passed through.

they hastily went on the air, as they like to put it, soon after radio astronomers discovered what they thought might be a strong gravity wave emitter—a neutron star spinning a record 642 revolutions per second. Unfortunately, the cause of this high-speed rotation was not as predicted, making the star a dud as a gravity wave source.

"Of course, we're merely in our infancy compared to the bars," says Spero. A row of empty champagne bottles in Whitcomb's office marks off their progress toward ever greater sensitivities; they add one bottle each time they increase sensitivity by 10. At present, the Caltech system can measure a quiver in the space between the masses of less than one ten-trillionth of a centimeter. But they'll need a tenfold to thirtyfold improvement to match the Stanford detector.

The Caltech gravity wave astronomers will become worthy contenders if some $50 million in funding allows them to fulfill their ultimate goal: construction of two mammoth laser systems, each with arms stretching out some three miles. They're collaborating on this ambitious proposal with Weiss's gravity wave group at MIT. Each will look more like an atom smasher than an astronomical instrument, only in this case, beams of light instead of beams of particles will be running down the giant tubes. "We'll need a quiet place," says Drever. "Perhaps a desert or even an underground mine." Separating the twin detectors by at least a thousand miles will enable them to filter out local noises and so better check for real coincident pulses, a must in any serious search for gravitational waves.

It won't stop there. Eventually gravity wave astronomy is destined to take to space. Just as electromagnetic radiation comes in all sizes from radio waves to gamma rays, gravity waves will certainly vary in length, depending on the source. Collapsing stars, for example, are expected to send out ripples that stretch some 200 miles from peak to peak. But if a supermassive black hole residing in the core of an exploding galaxy gobbles up a

Logic and ingenuity are essential in solving sensitive design problems, but a sense of humor can't hurt. All three are evident in the Caltech solution to the problem of eliminating extraneous vibrations in their system: The frames that hold the masses are stabilized with alternating layers of rubber toy Mercedes Benzes and dune buggies.

star, it might send out waves hundreds of millions of miles in length. Because the bars, like a tuning fork, respond to limited frequencies, these very long wavelengths will be best detected by laser systems—especially spaceborne systems, which have even longer arms.

Actually, some tentative gravity-wave tests have already been made far above Earth's atmosphere. For six days in March 1980, scientists from the Jet Propulsion Laboratory and the radio astronomy department of Caltech monitored the radio signals flowing to and from the *Voyager 1* space probe during its sojourn to the outer planets. If a gravity wave had rolled by, it would have varied by about a millimeter that vast distance between our planet and *Voyager 1*, and this would have shown up as an advance or delay in the phase of the spacecraft's radio signal beaming back toward Earth.

Some hope in this way to measure the general background of gravity waves out in space. Such a murmurous hubbub is more important than it sounds. Our explosive beginning, the Big Bang that occurred some 15 billion years ago, may have emitted a burst of gravitational radiation that echoes through the universe to this day. The *Voyager 1* test didn't find it, nor have tests with Pioneer spacecraft, which have been tracked for three weeks each year since 1981. But a more sensitive attempt will be made as the U.S.'s next interplanetary probe, the Galileo spacecraft, flies out to rendezvous with Jupiter in a couple of years.

There are also plans to send an entire laser system out into space (see illustration opposite), but meanwhile scientists are still working hard to produce results from earthbound systems. At present, an array of Stanford-type bar detectors could conceivably detect a supernova popping off in our Milky Way, and the gravitational pulse could be as revealing as a motion picture of the collapse itself. "There's just no other way for us to see this," says Thorne, "since the electromagnetic waves emanating from the core are completely absorbed by the outer layers of the star." Gravity waves, on the other hand, can travel from the stellar heart with impunity. The wave pattern might even reveal the core of the supernova bouncing for a brief moment—squishing down like a pancake and then stretching out like a football before settling down.

But there's a catch. Astronomers estimate that such stellar explosions, and the resulting collapse of the remnant cinders into ultradense neutron stars or black holes, occur in our galaxy only once every 30 years. Even improving the detectors to see out to the Virgo cluster would provide only a few events a year. That's small reward for such a complex enterprise. "But the universe always turns out to be more complicated than we originally think," Fairbank quickly counters. "People almost didn't want to look for X rays in space, believing they just weren't there."

Theorists are sure the same is true for gravitational waves. During the last decade, they've come to suspect that a whole circus of gravity-wave emitters lurk in the heavens:

■ Binary neutron stars. Several years ago, astronomers from the University of Massachusetts at Amherst discovered that our Milky Way harbors a most interesting stellar couple: two neutron stars orbiting one another about once every eight hours. And the fact that this orbital period is inexorably decreasing is indirect evidence that the binary system is emitting some energy in the form of gravitational radiation. "This type of system is our one, fairly sure bet," says Caltech's Kip Thorne. Current gravity wave detectors are too crude to sense this continuous, weak emission. But when those six-mile-wide balls of compact matter finally spiral into one another, they'll release a sizable burst. That isn't likely to happen in the Milky Way anytime soon; the next clash here may be 300 million years from now. "But in the 1990s the Caltech-MIT laser system might be able to see this type of event out to a billion light-years," says Thorne. "At that distance, it's reasonable to expect an event a week."

■ Deformed neutron stars. If a city-sized neutron star develops a blemish on its surface—an inch-high "mountain," for instance—it will continually transmit gravitational waves as that bump rapidly spins round with the star's rotation.

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—*William Fairbank*

"And sudden changes in the frequency of that signal," says Thorne, "would pinpoint 'starquakes,' enabling us, in collaboration with radio, optical, and x ray astronomers, to study the inner dynamics of a neutron star. In a sense, the gravity wave antenna would be used as a stellar seismometer."

■ Colliding black holes. "This is my favorite event in terms of the physics that could be learned," says Thorne. "If I had to lay bets on how we'll finally get 100 percent proof that black holes exist, it would be this." Black holes, of course, are those alleged celestial objects so dense that no bit of light or matter can escape their powerful gravitational grip. And if two of them should be orbiting one another, they will eventually spiral in, releasing a unique set of gravitational waves: first, an ever higher pitched whine during the final minute of the fateful twirl, then a cymbal-like crash as the holes coalesce, and finally a ring-down as the merged holes settle down. Gravity wave antennas that are now on the drawing board have a good chance of seeing these momentous collisions out to the edge of the visible universe. With such a large vista, they could perhaps even see several a day.

"But if I bet money on the first event to be seen," says Thorne, "I'd say it's going to be something we haven't even thought of," just as quasars (highly energetic galaxies located at the edge of our visible universe) had not been imagined by even the most farsighted of science fiction writers before the birth of radio astronomy.

Since spurious blips are being received by some detectors now, how will everyone agree that a gravity wave has actually traveled through our neck of the celestial woods? "It would be nice if, one day, four bar detectors and two big laser systems simultaneously detected a pulse, then three days later a supernova were observed in our galaxy," answers Whitcomb. "That would be the 'Eureka' scenario."

But it's probably wishful thinking. "More likely," he says, "it will be a slow consensus."

It's a gentlemanly race, even though the contenders in this field are not unaware that a Nobel Prize may be their reward. Yet, there are still some curmudgeons in the astronomical community, albeit just a few, who wonder if it's worth the intricate fuss right now, especially since the first gravity wave has yet to be clearly detected.

Fairbank has no such qualms. This courtly scholar, who has already dedicated more than a decade to this chancy endeavor, has a ready answer to these doubting Thomases: "Some of my colleagues remark, 'Why do you want to bother working on gravity waves? You don't know when you'll see a signal.' But I say it's not a gamble. Technology is allowing us to look into regions where we've never looked before. The real objective is not just the race to see who detects gravity waves first, although it's always fun and rewarding when you see something first. Actually, it's the chance to open this new window on the universe. This is the time of one of the greatest opportunities in physics." ■

Peter Bender, James Faller, and Dieter Hils of the Joint Institute for Laboratory Astrophysics in Boulder, Colorado, have a bold vision for future gravity wave detection: a laser system in space. In this plan, three spacecraft would orbit the sun in formation, and laser beams would indicate any change in distance between the units.