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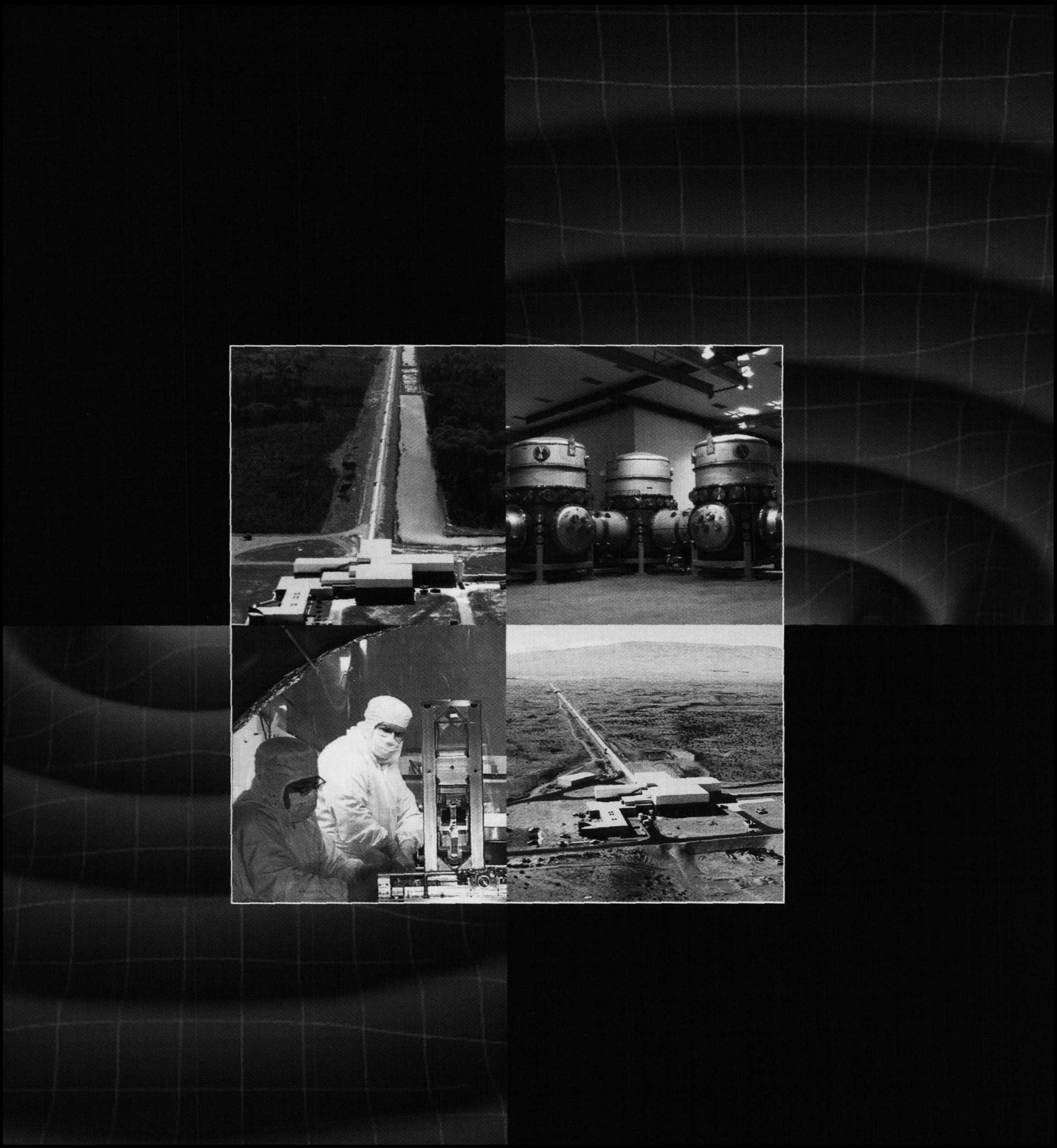
CATCH A GRAVITY WAVE

Two sprawling observatories in Washington and Louisiana will test one of Einstein's great theoretical predictions.

by Marcia Bartusiak

The Hanford Nuclear Reservation, currently the nation's prime repository for nuclear waste, sprawls over hundreds of square miles of scrub desert in south-central Washington state. The nearest town, Richland, is 10 miles away. At a key intersection, the road signs direct travelers to either continue west or turn south. There is no sign at all to explain the highway going north, the entrance to the reservation. It is a leftover habit from Hanford's many years as a national secret during World War II.

Five miles down that desolate road resides the Laser Interferometer Gravitational-Wave Observatory operated by the California Institute of Technology and the Massachusetts Institute of Technology. Those in the know simply call it LIGO (pronounced LIE-go). It is a rent-free guest on the Hanford site. Standing alone on the vast plain, a landscape long ago carved flat by the immense outflow of an ancient glacial lake, the complex resembles either a tasteful warehouse or a modern art museum inexplicably



Previous page, clockwise from upper left: The Louisiana LIGO seen from the air; vacuum chambers that hold LIGO's delicate optics; the Washington LIGO seen from the air; LIGO researchers in "bunny suits" setting up optics so the light beams will be properly aligned. Caltech/MIT/LIGO

placed in the middle of nowhere. An exact duplicate, painted in the same hues of cream, blue, and silver gray, can be found in the pine forests of Livingston Parish in Louisiana, outside Baton Rouge. Together, they form an astronomical tool of the 21st century, a detector like no other before it.

The signals these two observatories seek are waves of gravitational radiation, or more simply gravity waves, as they are better known in the popular media. Electromagnetic waves, be they visible light, infrared light, or radio waves, are produced by molecules, atoms, or electrons and generally reveal a celestial object's physical condition — how hot it is, how old it is, or what it is made of. Gravity waves will not convey such information. Instead, they will tell us about the motions of massive celestial objects. "It's both an exciting and overpowering change," says Gary Sanders, LIGO's deputy director. "There's almost a romantic attraction, this chance to look at a whole new window of the universe."

SPACEQUAKES

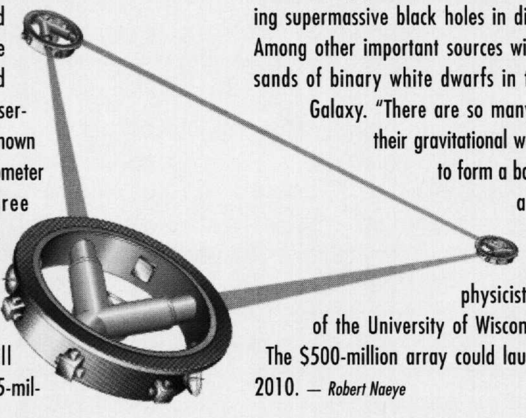
Gravity waves are literally quakes in spacetime that emanate from the most violent events the universe has to offer — a once blazing star burning out and going supernova, the dizzying spin of neutron stars, or the cagey dance of two black holes whirling around each other, approaching closer and closer until they merge. Gravity waves will tell scientists how large amounts of matter move, twirl, and collide throughout the universe. Eventually, this new method of examining the cosmos may even record the remnant rumble of the first nanosecond of creation, the remains of the ultimate spacetime jolt of the Big Bang itself.

Inside LIGO's main halls, at both Hanford and Livingston, the ambiance is almost reverential, akin to the response one might feel inside a darkened telescope dome. But this astronomical venture is vastly different. There are no windows to spy on the universe. Instead, two 4-foot-wide tubes at right angles to each other extend out into the countryside for 2.5 miles (4 kilometers). Together, these arms form a giant L in the landscape. The tubes resemble oil pipelines, although they can't be seen directly. Six-inch-thick concrete covers protect them from the wind and rain. In Louisiana, the concrete has also stopped occasional stray bullets during hunting season. A hit could be devastating because the pipes are as empty of air as the vacuum of space. Indeed, they surround the largest artificial vacuum in the world.

These gravity-wave observatories are firmly planted on cosmos firma, awaiting their first rumbles, vibrations predicted by Albert Einstein 84 years ago. "The worship of Einstein is the only reason we're here," says Rainer Weiss of MIT, one of LIGO's founding fathers. "If you go to Congress and tell them you're going to try to show that Heisenberg's uncertainty principle is not quite right, you run into blank stares. But if you say you're measuring something that's proving or disproving Einstein's theory, then all sorts of doors open. There's a mystique."

LISA

As scientists build LIGO and three other laser interferometers in Italy, Germany, and Japan, an international collaboration of American and European physicists are planning a space-based gravitational wave observatory affectionately known as LISA (Laser Interferometer Space Antenna). Three identical spacecraft will fly in an equilateral triangle formation far from Earth. Each spacecraft will fire a 3-million-mile (5-million-km) long laser beam toward one of its partners. This long reach will enable LISA to "hear"extremely low-frequency gravitational waves emitted by merging supermassive black holes in distant galaxies. Among other important sources will be the thousands of binary white dwarfs in the Milky Way Galaxy. "There are so many of these that their gravitational waves will merge to form a background noise at very low frequencies," says physicist Patrick Brady of the University of Wisconsin-Milwaukee. The $500-million array could launch as soon as 2010. — *Robert Naeye*

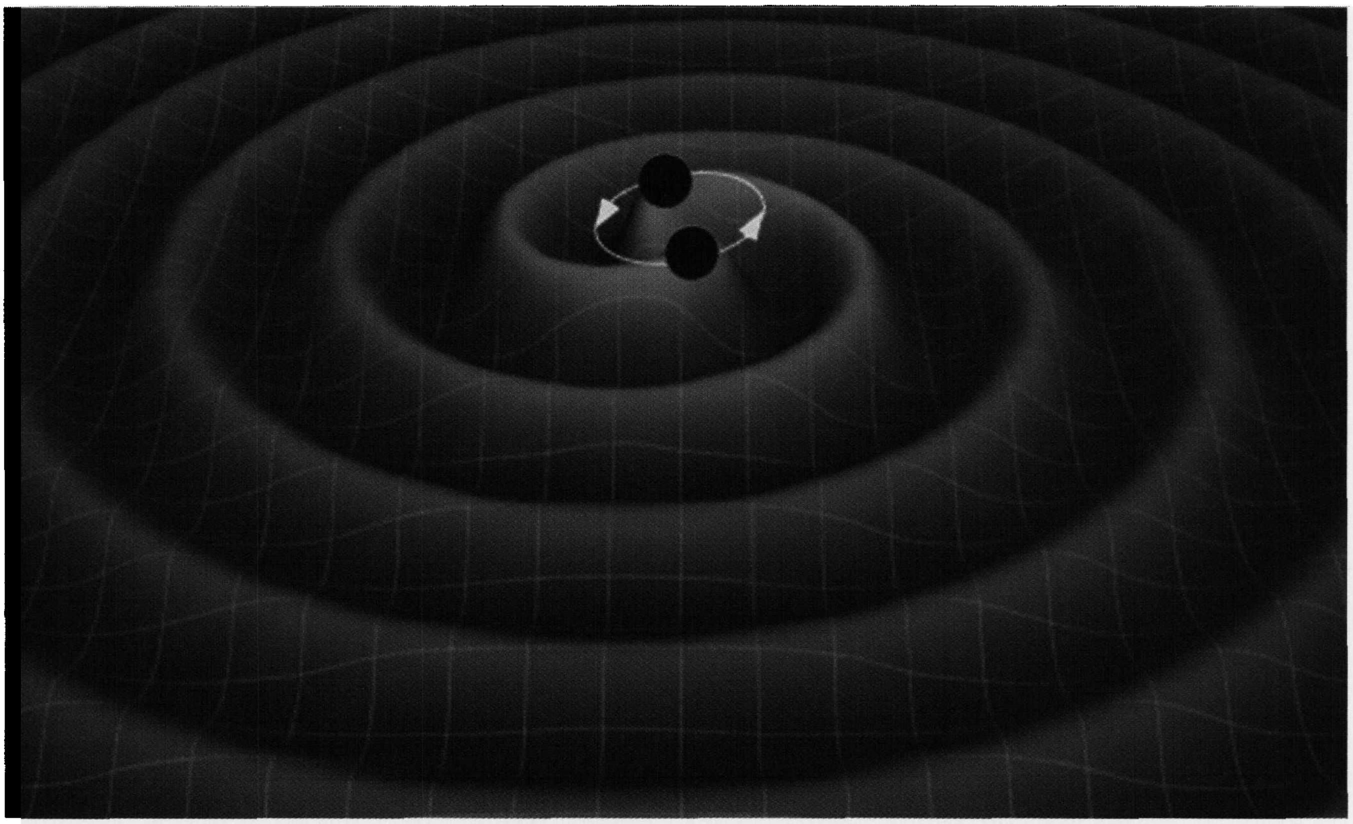


William Folkner (JPL)/NASA

Einstein unleashed a revolution that altered the commonplace notions of space and time. His general theory of relativity showed that matter, space, and time are linked, producing the force known as gravity. Space and time are joined together into an entity known as spacetime, whose geometry is determined by the matter around it. According to general relativity, stars and other massive bodies dimple the spacetime around them, much the way a bowling ball creates a depression in an elastic mat. Planets and comets are attracted to the star because they follow the curved spacetime highway carved out by the stellar orb.

When it was first introduced in 1915, general relativity was hailed as a momentous conceptual achievement but thought to have little practical importance. How times have changed. Global Positioning Satellites, used regularly by hikers, sailors, pilots, and soldiers to keep track of their locations, continually require general relativistic corrections to keep in sync. Moreover, astronomers discovered intriguing celestial objects such as pulsars, quasars, and black holes that they could be understood only through the physics of general relativity. And yet the story of general relativity remains incomplete.

A major prediction of general relativity still awaits direct observational confirmation: gravitational waves. Einstein first mentioned them in 1916. He recognized that just as radio waves are generated when electrons travel up and down an antenna, gravity waves should be produced when masses move about. To understand this phenomenon, imagine one of the most violent events the universe has to offer — two supermassive black holes crashing into each other in the center of our galaxy. When this happens, space is shaken — and shaken hard. Such a colossal collision would send out a spacequake that surges through the cosmos at the speed of light. Its waves would not travel



As two black holes spiral inward toward a fateful merger, they radiate gravity waves.

Tim Carnahan (GSFC)/William Folkner (JPL)/NASA

through space in the manner a light wave propagates. Rather, they would be an agitation of space itself. The waves would alternately compress and extend the fabric of spacetime.

Such waves would be deadly near the crash site. They would stretch a 6-foot man to 12 feet and within a millisecond squeeze him to three, before stretching him out once again. Any planets in the vicinity would be torn asunder. Fortunately, by the time such waves reached Earth, this cosmic tsunami would be reduced to a subatomic flutter. Were such gravity waves to hit this page, they would be so weak that they would squeeze and stretch the sheet's dimensions by a distance thousands of times smaller than the size of a proton.

Almost no one doubts that gravitational waves exist, for there is already powerful evidence they are real. Two neutron stars in our galaxy are rapidly orbiting each other, drawing closer and closer together. The rate of their orbital decay — about three feet per year — is just the change physicists expect if this binary pair is losing orbital energy in the form of gravitational waves. Joseph Taylor and Russell Hulse won the Nobel Prize in 1993 for this discovery. Direct reception of a wave, though, would offer the ultimate proof and provide astronomers with one of the most radical new tools to explore the heavens in four centuries. This explains the motivation to construct LIGO, as well as similar instruments of varying sizes in Italy, Germany, and Japan.

THE GONG SHOW

This entire endeavor began modestly in the 1960s as one man's quixotic quest. University of Maryland physicist Joseph Weber cleverly surmised that a burst of gravitational energy should set a large cylindrical bar of aluminum vibrating, much like a gong continuing to ring after being struck, though far more weakly. When he reported a detection in 1969, others around the world quickly constructed bar antennae. While most physicists remained highly skeptical of Weber's detections, he initiated a new branch of physics that has never diminished.

The seeds of LIGO, a scheme different from Weber's, can be traced to a classroom exercise three decades ago. To teach the concept of gravity waves during a general relativity course at MIT, Weiss asked his students to envision three mirrors suspended above the ground, their orientation forming the shape of an L. One mirror would be in the corner, the others at each end. Weiss understood that as a gravity wave travels it does two things: The wave compresses space in one direction — say, north/south — while simultaneously expanding it in the perpendicular direction — east/west. A gravity wave coming straight down on this L-shaped set-up would squeeze one of the arms so the mirrors would be closer together, while spreading the mirrors in the other arm farther apart. A millisecond later, as the gravity wave continues onward, this effect would reverse, with the compressed arm expanding and the expanding arm contracting. Weiss was rediscovering an idea that Weber and others had thought of earlier, but Weiss carried out a detailed study that envisioned nearly all the crucial pieces of the observatories now coming on line.

Weiss figured that a laser beam, bouncing back and forth between the mirrors at each end of the L, could track a gravity wave's expand/contract flutters. The light would enter the corner of the L. A beam splitter would split the light into two beams, each directed down an arm. After multiple reflections off the mirrors, the beams could be recombined, at which time they interfere with each other (hence the term "interferometry"). The beams could be initially set so that their waves arrive out of phase. In other words, when added together, the waves from both arms would cancel each other out. When the crest of the light wave in one beam is added to the trough of the light wave in the other beam, the result is darkness, like adding 1 and –1 to get zero. But if a gravity wave causes the arms to expand or contract, the two laser beams would travel slightly different distances. In that case, the recombined beams will be more in phase and would thus produce some light. The gravity wave would be spotted in those light changes.

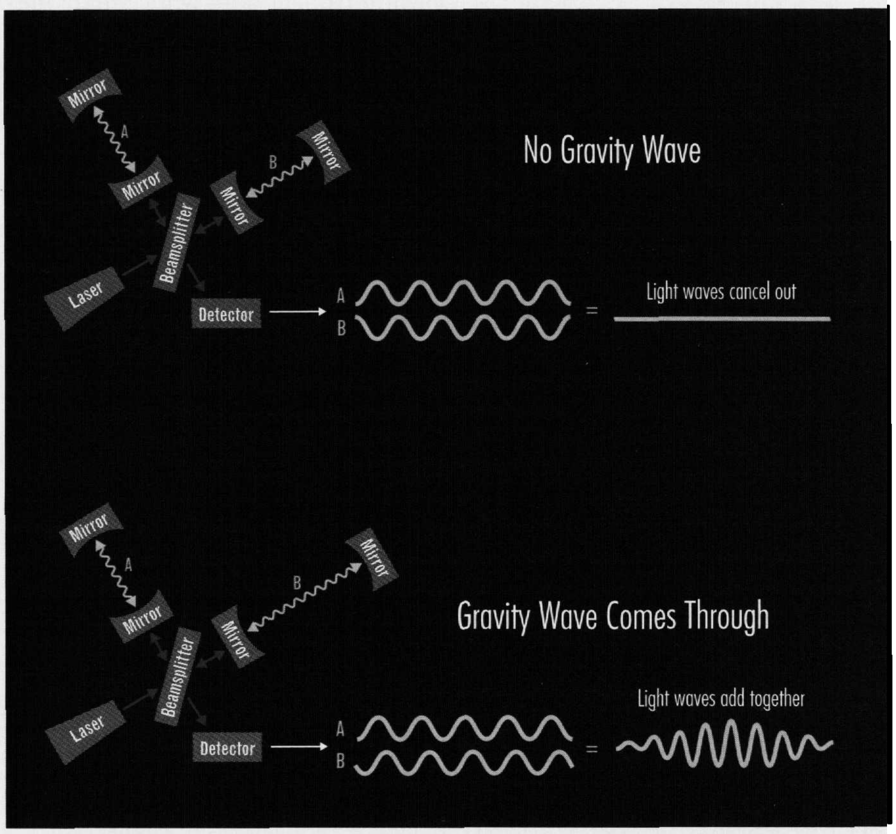
Weiss's concept caught on because it had a distinct advantage. A bar antenna can be tuned to only one gravity-wave frequency (as if it were a radio that could pick up only one station). A laser interferometer, on the other hand, is like a broad-band radio. It can detect a wide range of frequencies, making it more versatile for astronomy. Weber's protégé Robert Forward operated the first prototype, a small tabletop instrument, in 1972 at the Hughes Research Laboratories in California. Pioneering groups in Scotland and Germany went on to build interferometers with longer arms, making technological breakthroughs that at last allowed laser interferometry to surpass the bars in sensitivity. A turning point came in 1979 when Caltech lured the Scottish interferometry wizard Ronald Drever to its campus to build an instrument with 40-meter arms, the longest in its day.

FROM TEST BEDS TO TELESCOPES

But these were all test beds, not true gravity-wave telescopes. Detecting spacetime tremors requires interferometers with arms miles in length. The subatomic expansions and contractions are easier to measure over long distances. The longer the armspan, the greater the effect. When MIT joined forces with Caltech in 1983, they planned to build two large observatories.

But their funding did not arrive for nearly a decade. With no guarantee that a gravity wave would be detected, many astronomers and physicists waged a long, hard campaign against LIGO, declaring that the money would be better spent on surer scientific quests. But the potential of the science — not to mention strong politicking — eventually overrode those concerns.

If no gravity wave passes through one of the LIGO facilities, the two 2.5-mile arms have exactly the same length. Light beams reflecting within each arm will arrive at the detector out of phase, so they cancel each other out. If a gravity wave passes through, one arm will be lengthened and the other compressed by about the width of a proton. The changes in arm length cause the light to arrive at the detector partially in phase, so the beams add together to create a detectable signal.



With a final construction cost of $292 million (making LIGO the most expensive project ever funded by the National Science Foundation), the Hanford and Livingston observatories are separated by nearly 1,900 miles (3,000 km). The two are more like fraternal than identical twins. The Hanford facility actually houses two interferometers, which operate side by side through the arms. There is a full-length detector of 2.5 miles, as well as one half as long. The Livingston observatory has only the full-length interferometer. Each observatory, though, follows the same principles first established by Weiss, Drever, and others some three decades ago.

The mirrors, now two in each arm, are made of fused silica. Ten inches wide and four inches thick, each 22-pound (10-kg) cylindrical disk is polished to a smoothness that does not vary by more than 30-billionths of an inch. "If Earth were that smooth," notes LIGO's GariLynn Billingsley, who monitored the mirrors' production, "then the average mountain would not rise more than an inch." Such smoothness is a must for the light to be reflected over and over again to extreme accuracy. Each mirror is balanced on a single steel wire that is attached to a gallows-like frame. This support, in turn, rests on an isolation platform, not unlike a car's suspension system, to reduce seismic jitters by a millionfold.

Two observatories are needed to rule out local disturbances that might mimic a gravity wave at any one site, such as a passing garbage truck or seismic tremors. A gravity wave will pass through both observatories within 10 milliseconds of each other. In addition, the shape and size of the wave should be identical in both places.

LIGO will be most receptive to frequencies from 100 to 3,000 hertz, which is coincidentally the same frequencies our ears pick up as sound. You could actually listen to the signal, once it is electronically recorded. "It sounds like a hiss," notes LIGO's Albert Lazzarini. "Actually, it's a hiss with warbles in it due to the suspension. It's eerie, in some ways like whale songs." Gravity waves will at last be adding sound to our cosmic senses.

LIGO Detection Rates

Major upgrades scheduled to begin around 2005 should increase LIGO's sensitivity tenfold. These upgrades include a more powerful laser, better cushioning to shield against seismic vibrations, silica wiring, and pure sapphire mirrors. The black holes visible to LIGO will be in the range of a few dozen solar masses. The merger of two black holes that LIGO 1 at best could barely register at 300 million light-years should be readily detectable by LIGO 2 at 6 billion light-years. The numbers to the right display large ranges because they heavily depend on the theoretical assumptions, parameters that won't be known for sure until the first detections are made.

Event and Region of Space Scanned

LIGO 1	LIGO 2
Supernova (within our galaxy) 1 to 3 per century	Supernova (out to 60 million light-years) 2 to 3 per year
Black Hole/Black Hole Merger (out to 300 million light-years) 1 per 1,000 years to 1 per year	Black Hole/Black Hole Merger (out to 6 billion light-years) 10 per day to 10 per year
Neutron Star/Neutron Star Merger (out to 60 million light-years) 1 per 10,000 years to 10 per century	Neutron Star/Neutron Star Merger (out to 1.5 billion light-years) 1 per day to 1 per year
Neutron Star/Black Hole Merger (out to 130 million light-years) 1 per 10,000 years to 10 per century	Neutron Star/Black Hole Merger (out to 3 billion light-years) 10 per day to 1 per year

Computers, not ears, though, will be sifting through LIGO's data. The technique will be similar to the way in which military sonar experts search for the distinctive sound of a submarine amid the many noises of the sea. Essentially, as the data stream comes in, it will be compared to a "template," a theoretical prediction of what a gravity-wave signal might look like. Take, for example, the case of two neutron stars spiraling into each other. According to computer simulations, this system can produce many possible wave patterns because the signal depends on both the masses of the neutron stars and their orientation as viewed from Earth. To do a proper search, LIGO will have to continually compare its stream of data against some 20,000 to 30,000 possible signal patterns worked out by theorists.

Neutron star collisions may be the bread and butter of LIGO's trade. Once the detectors are sensitive enough to see hundreds of millions of light-years beyond Earth, they may detect a few mergers per year. LIGO will register the binary's final minutes, a sort of whine that rapidly rises in pitch, like the sound of a swiftly approaching ambulance siren, as the two city-sized balls of dense matter spiral into each other.

The biggest prize of all will be two black holes colliding. As the twirling holes are about to meet, spiraling inward faster and faster at speeds close to that of light, computer models predict that the whine will turn into a chirp, a birdlike trill that races up the scales in a matter of seconds. A cymbal-like crash, a mere millisecond in length, heralds the final collision and merger. The two black holes become one. A ring down, akin to the diminishing tone of a struck gong, follows as the new black hole swirls around like the fearsome tornado in *The Wizard of Oz*, wobbles a bit, and then settles down. Such a sighting would be the first direct evidence that black holes truly exist.

Other potential signals include the explosive burst of an asymmetric supernova, a murmur from the Big Bang itself, and the steady beat from a rotating neutron star. "But what if the strongest gravitational-wave signal," asks Lazzarini, "is a belch or burp that arrives sporadically? Then what? You have to assure yourself it wasn't just an amplifier problem or a bad wire." Those sorts of signals, the unexpected or irregular, will be the most difficult of all, "but they're also where the biggest surprises and most profound discoveries may lie," adds Lazzarini.

FIRST LIGHT

When new optical telescopes come on line, there is usually a celebratory "first light" event, the moment when the instrumentation is turned on and the first picture taken. LIGO's construction was completed last November, but its initiation was not so dramatic. Because its engineering and optics are so complex, LIGO will require a few years for its initial shakedown and calibration before all three interferometers — the two at Hanford, the other in Louisiana — can work in concert with one another. Then and only then can the search for gravity waves really begin, perhaps by late 2002.

LIGO researchers concede that their first detectors may not register a thing. For its critics, that made LIGO technologically unjustifiable and premature. LIGO, however, was built on the belief that scientists and engineers couldn't have found solutions without first building a full-sized facility to carry out the needed tests. At first, the two interferometers will be able to detect a change in spacetime as small as a millionth trillionth of a meter. Even then, the observatories will have only a small chance at observing an event. Over the years, upgrades will increase sensitivities more than tenfold, enabling LIGO to "feel" spacetime rumbles emanating from a variety of sources hundreds of millions or even billions of light-years distant. An advanced LIGO might register an event a day.

But what keeps LIGO researchers at work when no signal is guaranteed? "People take pleasure in solving the technical challenges," answers physicist Peter Saulson of Syracuse University, "much the way medieval cathedral builders continued working knowing they might not see the finished church. But if there wasn't a fighting chance to see a gravity wave during my career, I wouldn't be in this field. If you do this, you have the right stuff."

Marcia Bartusiak, a member of Astronomy's *editorial advisory board, adapted this article from her latest book,* Einstein's Unfinished Symphony, *which will be published this fall.*

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Visit our website at www.astronomy.com to hear the "sounds" of gravitational waves.