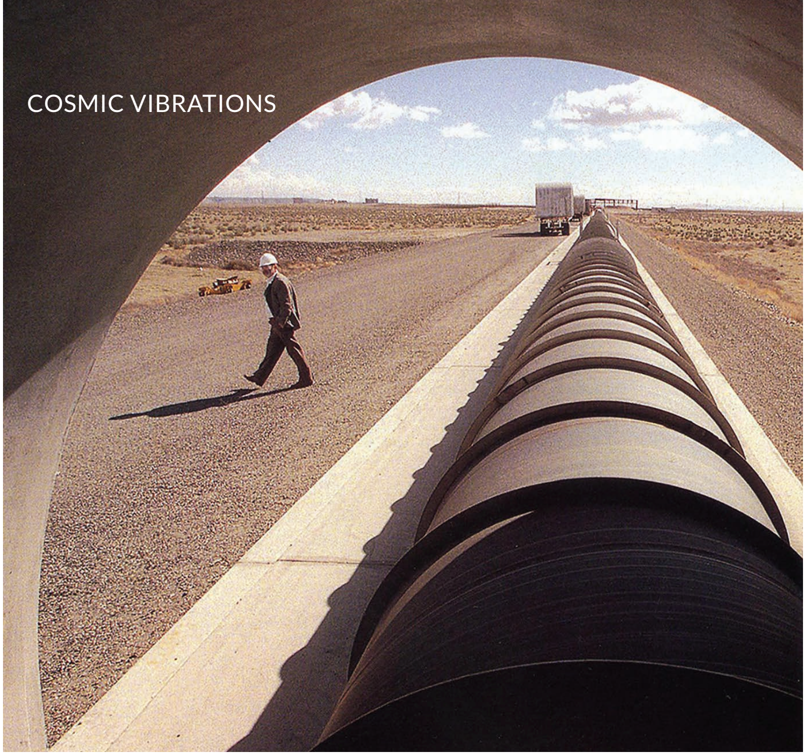
COSMIC VIBRATIONS



Two stainless steel tubes, 4 kilometers long, house laser beams and mirrors to detect waves from space at a LIGO site in Hanford, Wash.

BENJAMIN BENSCHNEIDER/*THE SEATTLE TIMES*

Listening for GRAVITY WAVES

The long road to detecting rumbles in the fabric of spacetime

By Marcia Bartusiak

The January e-mail from Syracuse University physicist Peter Saulson caught me off guard. It probably shouldn't have, since I had been anticipating the news for 16 years, ever since I wrote *Einstein's Unfinished Symphony*. The book chronicled the astrophysical community's most cutting-edge start-up: gravity wave astronomy.

Saulson's message meant that Einstein's symphony is no longer "unfinished." A gravitational wave (gravity wave in common parlance), the historic prediction arising from Einstein's equations of general relativity, had never been detected directly. But now, thanks to two colliding black holes, that unfinished task was finally completed, after decades of blood, sweat and immeasurable frustrations. It took that long to get a gravity wave detector working. More than that, the discovery's announcement (see Page 6) was made almost exactly 100 years after Einstein wrote his first paper on gravity waves. "As if those black holes were waiting for that moment," Saulson says.

In papers published in the *Proceedings of the Royal Prussian Academy of Sciences* in 1916 and 1918, Einstein reasoned that just as electromagnetic radiation, such as radio waves, is generated when electric charges travel up and down an antenna, waves of gravitational radiation (what he called *gravitationswellen*) must also be produced when masses move about.

But these waves do not travel through space the way light does; they are literally quakes in spacetime's very framework. Detectable rumbles emanate from the most violent events the universe has to offer — such as the ferocious encounter of two massive black holes (recorded by two gravity wave observatories) merging in a fateful embrace about 1.3 billion years ago. Alternately stretching and squeezing space, the wave right at the clash of the black holes would have stretched a 6-foot man to 12 feet and within a millisecond, squeezed him to 3 feet, before stretching him out once again.

Einstein never imagined such outrageous sources for his waves. Given the relatively quiet nature of the universe assumed in the 1910s, he was picturing waves rippling outward as two stars simply orbited one another. And he and others knew that those spacetime ripples would be feeble, certainly too weak to bother looking for them. Others wondered if his *gravitationswellen* didn't exist at all and were rather just imaginary artifacts of the relativistic mathematics. General relativists argued back and forth over this issue for many years.

Hope and disappointment

But the stalemate shifted in the late 1950s, when a young University of Maryland physicist named Joseph Weber decided to build a gravity wave detector to settle the question. Experimental relativity was undergoing a renaissance at this time, and Weber had been encouraged by Princeton physicist John Archibald Wheeler, then the dean of American general relativity, to hunt for an actual wave.

For his design, Weber surrounded a solid, water heater–sized cylinder of aluminum — a bar — with sensors, figuring that a passing wave would cause the bar to resonate like a bell. The sensors would convert the oscillations into electrical signals registered on a paper chart recorder. Two detectors separated by hundreds of miles, he reasoned, were needed to rule out local noises. In 1969, Weber grandly proclaimed at a relativity conference in Cincinnati that he had simultaneously recorded a signal on two bars, one on the Maryland campus, the other at Argonne National Laboratory near Chicago. Conferees greeted his announcement with applause (*SN: 6/21/69, p. 593*). The popular press heralded his find as the most important event in physics in half a century. “Many laymen will be startled, no doubt,” reported the *New York Times*. A year later, Weber declared that the signal was emanating from the center of the Milky Way galaxy, possibly from a supernova going off or maybe from pulsars, the rapidly spinning neutron stars that had been recently discovered.

Soon other physics groups built their own detectors. They detected no waves whatsoever. Yet they didn't give up. By the 1980s, teams in various countries had constructed even bigger bar detectors to increase sensitivity. They adjusted the designs, encasing detectors in supercooled fluids to reduce thermal noise. But, again, no signals were recorded. While Weber is still credited with jump-starting the field, the lack of verification damaged his reputation, although he insisted until his death in 2000 that his detectors were recording waves. Today, physicists put the claim down to noise and believe Weber didn't fully understand the natural noises emanating within his bars.

But while the bar technology was maturing, a new gravity wave–detecting strategy surfaced — a method known as laser interferometry. Two researchers in the Soviet Union, Mikhail Gertsenshtein and V.I. Pustovoit, first published the idea in 1962, but no one outside their country became aware of it. Weber, too, briefly thought of the technique but never published. In 1966, Rainer Weiss at MIT also came up with the scheme independently — and in an offbeat way.

Bouncing lasers

Asked to teach a course on general relativity, Weiss, who worked on gravity as an experimentalist, not a theorist, scrambled. “I couldn't admit that I didn't know it. I was just one exercise ahead of my students,” he said in 1999. Arriving at the topic of gravity waves, and wanting to understand them from a more hands-on perspective, he came up with a homework assignment. Imagine, he told his students, three masses suspended above the ground, their orientation forming an L shape. How would the distances between those masses change as a gravity wave passed by? He knew that a gravity wave compresses space in one direction (say, north-south), while expanding it in the other (east-west). A millisecond later, as the wave passes by, the effect reverses. By the time Weiss worked out the solution for himself, he knew that he had a darn good experiment in mind. Continually bounce laser beams between the masses, have the beams eventually recombine (optically “interfere” with one another) to measure the gravity wave shifts, and you have a detector! And it had one great advantage over the bars. Whereas bars could be tuned to only one frequency, laser interferometers could register a wider range of frequencies, increasing the chances of detecting a source.

By 1972, Weiss had written a landmark report for MIT's Research Laboratory of Electronics identifying all the fundamental sources of noise that could mask a signal in such a setup. The paper is still consulted today by gravity wave researchers. From that point on, Weiss devoted a large part of his career to getting a laser interferometer constructed and to finding the means to reduce those noises. There was extra incentive to do so: In 1974 radio astronomers Joseph Taylor and Russell Hulse, then at the University of Massachusetts Amherst, found a neutron star orbiting a dense companion, the two drawing closer and closer by about a few meters each year — just the change in distance physicists expect if the binary pair is losing orbital energy as gravity waves. Though the proof was indirect (and the waves themselves too weak to measure), it greatly encouraged the gravity wave astronomy community that sources would be available.

By the 1980s, Weiss joined forces with Caltech theorist Kip Thorne, the world's top expert on the physics of gravity waves, and Scottish experimentalist Ronald Drever, also at Caltech, to leapfrog the small, laboratory prototypes being built and erect two sizable

The 100-year wait Physicists' efforts to detect gravity waves paid off one century after Einstein predicted the waves existed.

1915 Einstein presents his general theory of relativity

1916 Einstein writes papers in the *Proceedings of the Royal Prussian Academy of Sciences* describing the possibility of gravity waves

Late 1950s Joseph Weber begins work on a gravity wave detector

science news OF THE WEEK

Gravitational waves detected

A 10-year effort has found radiation many thought was too weak ever to be seen

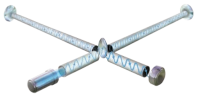
1966 Rainer Weiss at MIT conceives laser interferometry method to detect gravity waves

1969 Weber (pictured in *Science News*) announces detection of a gravity wave (it was never confirmed)

1974 Joseph Taylor and Russell Hulse find a binary pulsar system later shown to be losing energy consistent with the emission of gravity waves

1992 National Science Foundation selects sites in Washington and Louisiana for the Laser Interferometer Gravitational-Wave Observatory, or LIGO

1994 Construction begins at the two LIGO sites



2001 LIGO begins operating

2008 Construction begins on Advanced LIGO

2010 LIGO ends operations; Advanced LIGO installation begins

September 2015 Advanced LIGO begins observations and detects a wave

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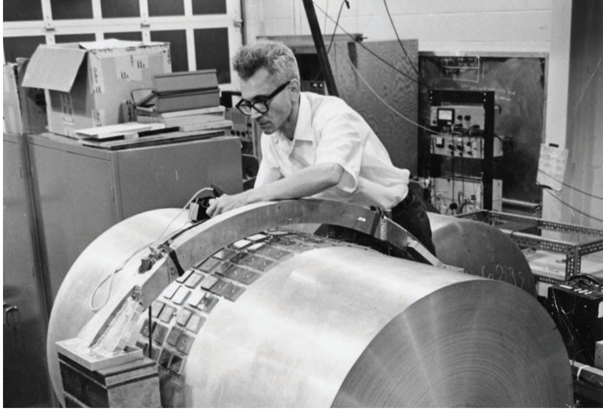


Joseph Weber, in 1969, working on his gravity wave detector at the University of Maryland in College Park.

detectors with lengthy arms instead. A nearly simultaneous reception at a pair of detectors set far apart geographically would verify a wave passed through at the speed of light. Increasing the laser light's path in the arms would magnify the detector's sensitivity. Astrophysical sources, such as supernovas exploding or black holes colliding, generate ripples in spacetime that would be deadly near the event, but by the time those waves reach Earth, they would wiggle the interferometer masses less than the width of a proton. Kilometers-long arms would be needed to measure such subtle movements.

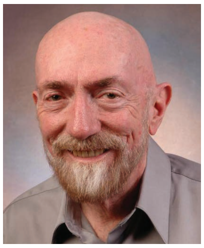
A feasibility study for this daring proposal (later dubbed the Laser Interferometer Gravitational-Wave Observatory) was completed in 1983. The report ultimately convinced the National Science Foundation (in particular NSF administrators Marcel Bardon and Richard Isaacson) to take a chance on going big. But so high was LIGO's estimated construction cost (it rose to nearly $300 million) that it was the first time that the NSF had to go to Congress to get approval for a project. When astronomers and physicists heard about the proposal, a few became very vocal, angered that the NSF was proposing to use precious funds on a gamble rather than a proven technology. As a result, the LIGO proposal went through innumerable ups and downs and was almost canceled more than once (*SN: 6/26/93, p. 408; SN: 1/8/00, p. 26*).

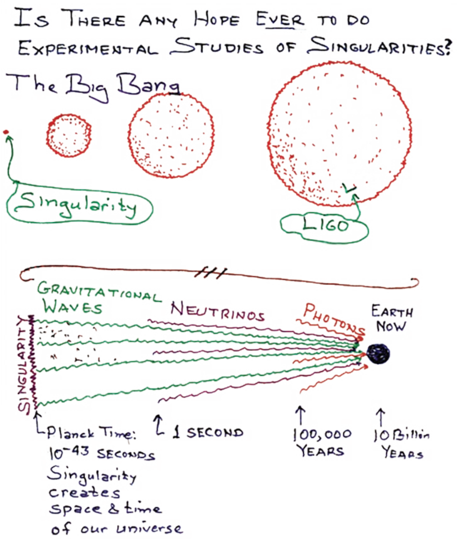
A crucial turning point occurred in 1992 when Caltech physicist Rochus Vogt, then the LIGO director, wrangled a meeting with Louisiana Sen. J. Bennett Johnston, who later became an ardent supporter of the project. Vogt originally had only 20 minutes, but his tales of cosmology so captivated Johnston that the senator canceled his next three appointments. For several hours, the two huddled over the senator's coffee table, while Vogt drew pictures of curved spacetime. Once again, Einstein's name worked magic. Congress eventually authorized funds to build two detectors, each with 4-kilometer-long arms: one situated in Livingston, La., the other 1,900 miles to the northwest in Hanford, Wash.

Ground was broken for those first-generation detectors in 1994. Both were up and running by 2001. Primarily a test bed to try out the novel technologies needed to find a gravity wave, the first LIGO wasn't expected to register any waves. But it still did its job. What LIGO collaborators learned from each detector's performance went into the design of innovative instrumentation, which was gradually installed over the last five years. This upgrade, called Advanced LIGO, led to an increased sensitivity that, bingo, found a gravity wave as soon as it began operation last fall.

Instruments around the globe are already joining LIGO's quest. A LIGO-like detector known as VIRGO, run by a European collaboration, has been operating on the vast alluvial plain outside Pisa, Italy, since 2007. (VIRGO was offline for instrumentation improvements when Advanced LIGO registered its first gravity wave.) A smaller interferometer named GEO600, with 600-meter-long arms, operates in Germany. Other detectors are under construction in Japan and planned for India.

But laser interferometers on Earth are limited in the frequencies they can register (roughly 10 to several thousand hertz), much the way an optical telescope cannot see radio waves or X-rays. To expand that range so gravity wave events from a variety of sources can be detected, gravity wave astronomers are





Kip Thorne (above) drew this sketch of gravity waves being emitted from the Big Bang for a 1999 lecture.

FROM TOP: SPECIAL COLLECTIONS/UNIV. OF MARYLAND LIBRARIES; CALTECH; K. THORNE/CALTECH

pursuing other methods as well. One clever scheme is based on well-studied astronomical objects — pulsars, the most exquisite timepieces in the universe due to the unvarying rhythm of beeps emitted by the rapidly spinning neutron stars (*SN: 10/17/15, p. 24*). By closely monitoring the pulses arriving from an array of particularly fast pulsars situated around the sky, astronomers are on the lookout for slight changes in the pulsing due to an extremely low-frequency gravity wave (10^{-9} to 10^{-6} hertz) passing between the pulsar and the earthbound detector. Supermassive black hole binaries would emit these tremendously long waves as they slowly orbit in the centers of merging galaxies. And ultimately, researchers hope to send laser interferometers into space. The European Space Agency is working on a proposal called the Evolved Laser Interferometer Space Antenna (*SN Online: 12/3/15*), which would enable the detection of weaker gravity waves.

A new astronomy

What the world is witnessing is the birth of a new astronomy. Detecting the ripples of those two black holes, uniting in the distant universe, is like Galileo's first peek at the heavens through a telescope in 1609. Galileo discovered moons orbiting Jupiter and jagged mountains and craters on the moon, amazing wonders to 17th century eyes. Now, gravity wave astronomy is poised to offer its own radically new visions.

Electromagnetic waves, be they visible light, radio, infrared or X-rays, are released by individual atoms and electrons. Such radiation reveals a celestial object's physical condition — how hot it is, how old it is, what it looks like and what it is made of. Gravity waves convey much different information. They will tell about the overall motions of massive objects, indicating how they move, twirl and collide throughout the universe, especially for objects that are too small to be seen directly, such as neutron stars and stellar black holes.

"We've now embarked on an era of exploring phenomena in the universe that are made from warped spacetime," Thorne says. "I like to call it the warped side of the universe." In due course, this new method of observing may be able to record the remnant rumble of the first nanosecond of creation, by gathering the residual gravity waves emitted by the awesome spacetime jolt of the Big Bang itself.

After more than four long and turbulent decades, Weiss has at last seen his experimental dream come true. Did he ever despair? "No," he says without hesitation today. "The reason you don't worry about the end result is this: The problems were interesting, you enjoyed the people you were working with, and it was fun to do!" Ever the experimentalist, Weiss, now 83, continues to travel to observatories, roll up his sleeves and check out the equipment.

He worked on the initial idea in the 1970s with just a few colleagues and students; today, more than 1,000 people are involved — LIGO/VIRGO collaborators at universities and institutes around the world advancing both the theory and the technology.

At the dedication of LIGO's Louisiana observatory in 1999, Rita Colwell, then director of the NSF, noted that those gathered were "breaking a bottle of champagne over the figurative bow of a modern-day galleon — a gravity wave observatory that may ultimately take us farther back in time than we've ever been." With their first signal, a crescendo that when converted to audio starts as a deep bass and heads toward middle C, LIGO scientists are beginning their journey, now able to listen for the myriad events that await detection.

With that in mind, I take back what I said at the opening to this essay. Einstein's symphony will never be finished. ■

Global gravity wave detectors

A global quest
Gravity wave detectors are operating in the United States, Germany and Italy, with two more in the works in India and Japan. Researchers expect an expanded network to improve detection confidence and source localization accuracy.

M. TELFER

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