Einstein's Symphony

The first chirp

Heading in from the southern sky at the speed of light, a gravitational wave passed through the Earth last September in less than a second. Such events have occurred ever since our solar system coalesced out of a nebulous cloud more than four billion years ago. But this time was different. This time that faint swell in space-time was finally snared by researchers, ushering in a new age of astronomy as game-changing as the one introduced by Galileo.

Einstein first mentioned the possibility of gravitational waves (or gravity waves, as they're more popularly known) one hundred years ago. He predicted that a pair of masses, such as two stars moving around each other, would undulate with the fabric of space-time. These waves then would move outward, much like the ripples generated when a stone is dropped into a pond, getting weaker and weaker as they spread. This pattern is far different from the way electromagnetic waves propagate. Light travels *through* space; gravity waves, by contrast, are vibrations *in* the very framework of space-time—compressing and stretching space-time (and any object caught within it) as they pass by.

Ever since the 1960s, scientists have been attempting to capture a gravity wave. At the University of Maryland, physicist Joseph Weber constructed the first detectors, large cylinders of metal, now called Weber bars, surrounded with sensors that he configured to "ring" like a bell whenever a gravity wave passed through them. He claimed to have observed such ringing a number of times, starting in 1969, but the detections were never confirmed. His effort, however, founded a new field of study, stimulating others to come up with new schemes.

In 1972, at the Massachusetts Institute of Technology (MIT), physicist Rainer Weiss wrote a landmark report, the first complete examination of an approach known as "laser interferometry." He suggested arranging a set of mirrors in the form of an L—one in the corner, the others at each end; continually bouncing laser beams up and down each arm to keep an accurate tab on the distance between them; and then having the beams recombine (optically "interfere" with one another) to check if a gravity wave had wiggled the mirrors.

Weiss and others built small laboratory prototypes, but the MIT physicist knew that no cosmic waves would ever be found unless the mirrors were separated by miles. The longer the distance, the greater the sensitivity of the measurement. By the 1980s, tired of his slow progress, Weiss joined forces with California Institute of Technology (Caltech) theorist Kip Thorne, the world's top expert on gravity waves, and experimentalist Ronald Drever, also at Caltech, to take a giant leap and seek National Science Foundation (NSF) funds to construct a pair of large detectors with two-and-a-half-mile-long arms, set geographically apart to rule out local noise.

Upon hearing of this proposal, the physics community quickly protested; it was aghast at the idea that the NSF might spend money on such a gamble when so much of the technology still needed to be invented. It was only after a decade of campaigning and politicking that the funds were finally approved and ground was broken for the Laser Interferometer Gravitational-Wave Observatory (LIGO) in 1994. One detector resides in Livingston, Louisiana, the other 1,900 miles northwest in Hanford, Washington. Turned on in 2001, and advanced and improved over the years, both instruments at last found their quarry on September 14, 2015.

The wave first arrived at Livingston two hours before dawn, at exactly 4:50:45 A.M. Central Daylight Time. Seven-thousandths of a second later, Hanford also sensed the wave. But the operators in the main control room at each site didn't notice. LIGO was then conducting an engineering run, a check on some newly installed equipment; data was being collected, but the sound alert, which goes off whenever a candidate signal passes a certain threshold, was not on. That awaited the official scientific run of the new, "advanced" detectors, which was set to occur the following day.

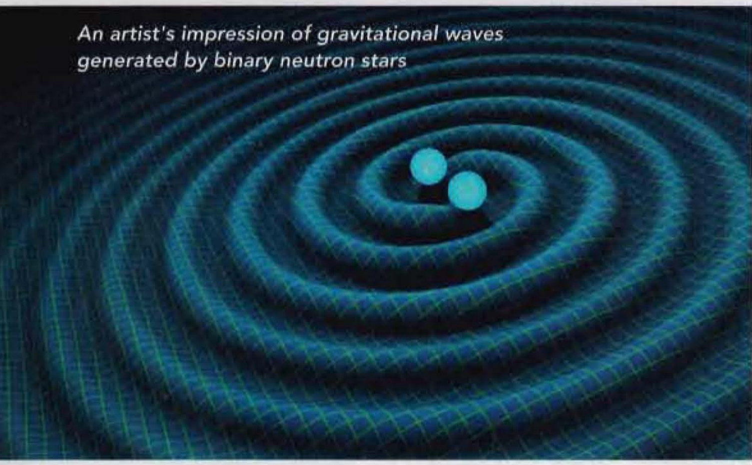
Instead, the data silently streamed into the automatic analysis pipeline, where, within a few minutes, the waveform popped up on the computer monitor of LIGO collaborator Marco Drago at the Albert Einstein Institute in Hannover, Germany. A member of LIGO's coherent wave burst group, the young post-doc was the first to see the signal. It was beautiful, clear, and strong. In fact, it was so picture-perfect that Drago and his colleagues, who soon gathered together, just assumed it was a "blind injection," someone from LIGO secretly sending out a fake signal to test the system. But they soon learned that wasn't the case. Could it have been a hacker? That, too, was a concern and, therefore, was thoroughly checked out. In the end, LIGO scientists finally realized they had their Cinderella scenario or "golden event," as Drago put it—a gravity wave always hoped for but never expected as a first detection. It stood high above the noise.

As LIGO continued to gather data (coming up with two more possible candidates as the months progressed), teams of theorists deciphered the inaugural wave's message according to Einstein's general theory of relativity.

HENZE/NASA

In less than a second, the signal had swept upward in frequency from 35 hertz (cycles per second) to around 250 hertz. Because that's the same frequency range as sound, it can be heard as a musical glissando that starts as a deep bass and swiftly ends near middle C. Gravity-wave astronomy is adding sound to our cosmic senses. This "chirp" was just the type of signal that would be expected to occur when two black holes, long orbiting one another, swirled together ever faster until they merged to form a single black hole. Such a collision had never before been demonstrated; the LIGO observations not only confirmed that it had occurred, but also indicated the sizes of the black holes. One of the holes weighed 36 solar masses, the other 29 solar masses. The resulting combined black hole, at 62 solar masses, was less massive than the sum of the two because some of the mass was instantly converted into pure gravitational-wave energy—fifty times more energy than all the stars in the universe were radiating at that moment. At the collision site, such a spacequake would be deadly, but by the time the waves reached Earth some 1.3 billion years later, they moved the LIGO mirrors a mere fraction of the width of a proton. That's why only gravity waves from the universe's most violent events are currently measurable.

And this detection was just the start. The LIGO instrumentation is continually being improved, so that it will be able to register more waves, arriving from even farther regions of the universe. A similar detector called Virgo, in Italy, will soon join them in the detection effort once its upgrade is completed. Gravity-wave astronomers expect someday to see events weekly, possibly even daily. Black-hole collisions are their big game, but other types of events are also expected to turn up. Kip Thorne describes them as "the warped side of the universe."


An artist's impression of gravitational waves generated by binary neutron stars

R. HURT/CALTECH-JPL

It's almost guaranteed the researchers will hear the resounding crash as two city-sized neutron stars—paired together in a binary system—spiral into each other as their orbital dance decays. Such events may turn out to be the bread-and-butter of these scientists' trade—and the most entertaining. Less dense than black holes, a pair of neutron stars will take longer to merge, so the final recordable signal might last minutes instead of fractions of a second. The gravity-wave "telescopes" will register a sinusoidal tune that sweeps to higher and higher frequencies as the two balls of pure neutrons spiral into one another. As soon as they touch, the two stars will be shredded to pieces, possibly releasing a burst of gamma rays. Computer simulations suggest they'll end up forming a black hole, but only their gravity waves can verify that.

There will be another type of signal in the gravity-wave sky, although far less frequent. A solitary tsunami of a wave may hit our shores whenever a star within our local galactic neighborhood explodes as a brilliant supernova. This happens when the star's nuclear core runs out of fuel, collapses, and sends out a shock wave and a flood of neutrinos that blows the rest of the star apart. Examining the gravitational waveforms from such a spectacular event will allow astronomers to see, for the first time, the birth of a neutron star or black hole.

All the while, playing in the background amid these chirps and pops, could be ongoing rhythms—a steady beat. When a neutron star forms, for instance, it might briefly vibrate and develop a bump on its surface, an inch-high "mountain" that freezes into place for a while. This deformation, jutting out like a finger, would send out a periodic gravity wave as it continually "scrapes" the space around it.

And beneath all those varied gravity-wave songs, astronomers expect an underlying murmur—constant, unvarying, and as delicate as a whisper. This buzz would be the faint reverberation of our universe's creation, its remnant thunder echoing down the passages of time. "That is the prize," says MIT physicist Nergis Mavalvala. That's because these primordial waves would bring us the closest ever to our origins, perhaps verifying that the universe emerged as a sort of quantum fluctuation out of nothingness.

Finally, there is the tantalizing prospect of encountering the unanticipated. Some theorists already wonder whether there might be relics from the early universe, highly energetic "defects" that were generated as the cosmos cooled down over its first second of existence. These include one-dimensional cosmic strings, extremely thin tubes of space-time in which the energetic conditions of the primeval fireball still prevail. Wiggling around like rubber bands, they would produce plenty of gravity waves. Not until astronomers scanned the heavens with radio telescopes did they discover pulsars and quasars. What else might be skulking about in the darkness of space, as yet unseen?

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