satellites, have been made that can be explained only if black holes really do exist. Furthermore, the observational tests of Einstein’s general theory of relativity have convinced even the most skeptical scientists that his picture of warped or curved spacetime is indeed our best description of the effects of gravity near these black holes.

24.7 Gravitational Wave Astronomy

Learning Objectives

By the end of this section, you will be able to:

- Describe what a gravitational wave is, what can produce it, and how fast it propagates
- Understand the basic mechanisms used to detect gravitational waves

Another part of Einstein’s ideas about gravity can be tested as a way of checking the theory that underlies black holes. According to general relativity, the geometry of spacetime depends on where matter is located. Any rearrangement of matter—say, from a sphere to a sausage shape—creates a disturbance in spacetime. This disturbance is called a **gravitational wave**, and relativity predicts that it should spread outward at the speed of light. The big problem with trying to study such waves is that they are tremendously weaker than electromagnetic waves and correspondingly difficult to detect.

Proof from a Pulsar

We’ve had indirect evidence for some time that gravitational waves exist. In 1974, astronomers Joseph Taylor and Russell Hulse discovered a pulsar (with the designation PSR1913+16) orbiting another neutron star. Pulled by the powerful gravity of its companion, the pulsar is moving at about one-tenth the speed of light in its orbit.

According to general relativity, this system of stellar corpses should be radiating energy in the form of gravitational waves at a high enough rate to cause the pulsar and its companion to spiral closer together. If this is correct, then the orbital period should decrease (according to Kepler’s third law) by one ten-millionth of a second per orbit. Continuing observations showed that the period is decreasing by precisely this amount. Such a loss of energy in the system can be due only to the radiation of gravitational waves, thus confirming their existence. Taylor and Hulse shared the 1993 Nobel Prize in physics for this work.

Direct Observations

Although such an indirect proof convinced physicists that gravitational waves exist, it is even more satisfying to detect the waves directly. What we need are phenomena that are powerful enough to produce gravitational waves with amplitudes large enough that we can measure them. Theoretical calculations suggest some of the most likely events that would give a burst of gravitational waves strong enough that our equipment on Earth could measure it:

- the coalescence of two neutron stars in a binary system that spiral together until they merge
- the swallowing of a neutron star by a black hole
- the coalescence (merger) of two black holes
- the implosion of a really massive star to form a neutron star or a black hole
- the first “shudder” when space and time came into existence and the universe began

For the last four decades, scientists have been developing an audacious experiment to try to detect gravitational waves from a source on this list. The US experiment, which was built with collaborators from the UK, Germany, Australia and other countries, is named LIGO (Laser Interferometer Gravitational-Wave Observatory). LIGO currently has two observing stations, one in Louisiana and the other in the state of Washington. The effects of gravitational waves are so small that confirmation of their detection will require simultaneous measurements by two widely separated facilities. Local events that might cause small motions within the observing stations and mimic gravitational waves—such as small earthquakes, ocean tides, and even traffic—should affect the two sites differently.

Each of the LIGO stations consists of two 4-kilometer-long, 1.2-meter-diameter vacuum pipes arranged in an L-shape. A test mass with a mirror on it is suspended by wire at each of the four ends of the pipes. Ultra-stable laser light is reflected from the mirrors and travels back and forth along the vacuum pipes (Figure 24.17). If gravitational waves pass through the LIGO instrument, then, according to Einstein's theory, the waves will affect local spacetime—they will alternately stretch and shrink the distance the laser light must travel between the mirrors ever so slightly. When one arm of the instrument gets longer, the other will get shorter, and vice versa.

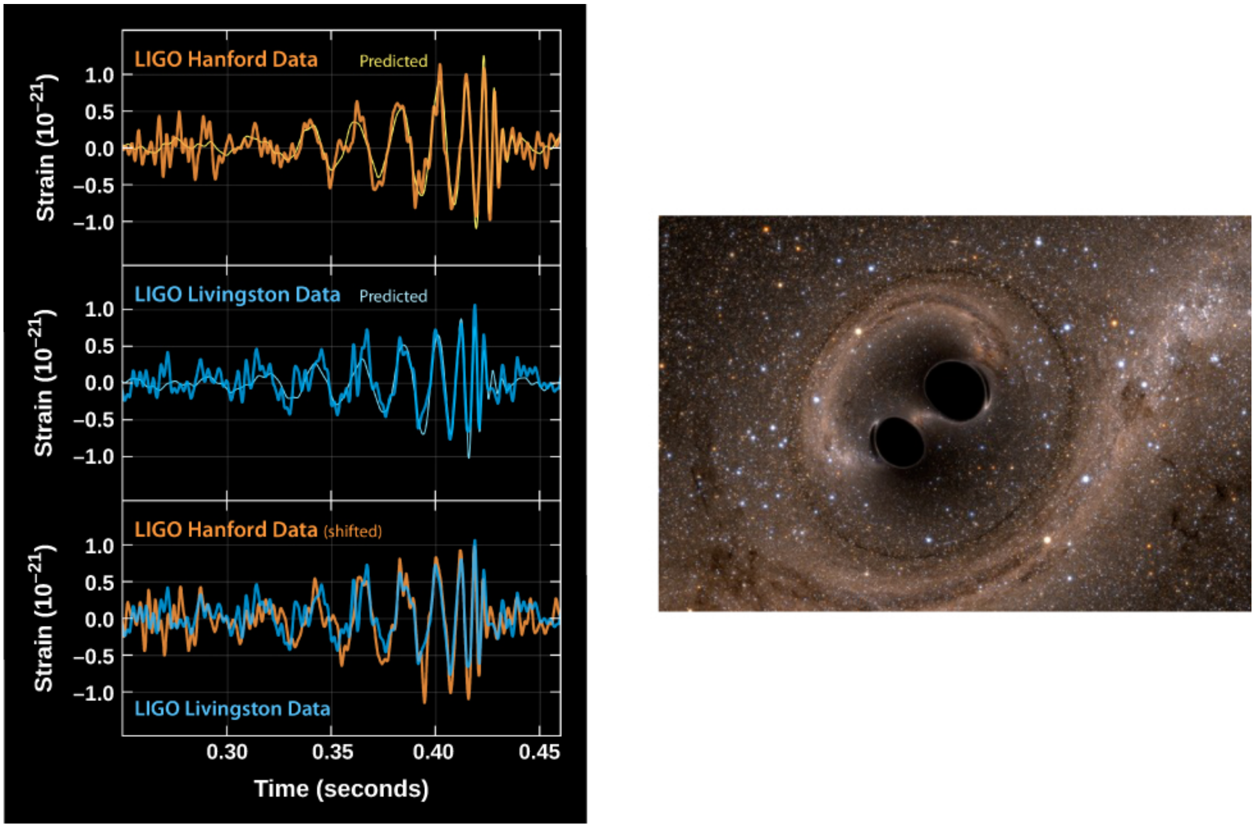
Figure 24.17 Gravitational Wave Telescope. An aerial view of the LIGO facility at Livingston, Louisiana. Extending to the upper left and far right of the image are the 4-kilometer-long detectors. (credit: modification of work by Caltech/MIT/LIGO Laboratory)

The challenge of this experiment lies in that phrase "ever so slightly." In fact, to detect a gravitational wave, the change in the distance to the mirror must be measured with an accuracy of *one ten-thousandth the diameter of a proton*. In 1972, Rainer Weiss of MIT wrote a paper suggesting how this seemingly impossible task might be accomplished.

A great deal of new technology had to be developed, and work on the laboratory, with funding from the National Science Foundation, began in 1979. A full-scale prototype to demonstrate the technology was built and operated from 2002 to 2010, but the prototype was not expected to have the sensitivity required to actually detect gravitational waves from an astronomical source. Advanced LIGO, built to be more precise with the improved technology developed in the prototype, went into operation in 2015—and almost immediately detected gravitational waves.

What LIGO found was gravitational waves produced in the final fraction of a second of the merger of two black holes (Figure 24.18). The black holes had masses of 20 and 36 times the mass of the Sun, and the merger took place 1.3 billion years ago—the gravitational waves occurred so far away that it has taken that long for them, traveling at the speed of light, to reach us.

In the cataclysm of the merger, about three times the mass of the Sun was converted to energy (recall $E = mc^2$). During the tiny fraction of a second for the merger to take place, this event produced power about 10 times the power produced by all the stars in the entire visible universe—but the power was all in the form of gravitational waves and hence was invisible to our instruments, except to LIGO. The event was recorded in Louisiana about 7 milliseconds before the detection in Washington—just the right distance given the speed at which gravitational waves travel—and indicates that the source was located somewhere in the southern hemisphere sky. Unfortunately, the merger of two black holes is not expected to produce any light, so this is the only observation we have of the event.



(a) (b)

Figure 24.18 Signal Produced by a Gravitational Wave. (a) The top panel shows the signal measured at Hanford, Washington; the middle panel shows the signal measured at Livingston, Louisiana. The smoother thin curve in each panel shows the predicted signal, based on Einstein's general theory of relativity, produced by the merger of two black holes. The bottom panel shows a superposition of the waves detected at the two LIGO observatories. Note the remarkable agreement of the two independent observations and of the observations with theory. (b) The painting shows an artist's impression of two massive black holes spiraling inward toward an eventual merger. (credit a, b: modification of work by SXS)

This detection by LIGO (and another one of a different black hole merger a few months later) opened a whole new window on the universe. One of the experimenters compared the beginning of gravitational wave astronomy to the era when silent films were replaced by movies with sound (comparing the vibration of spacetime during the passing of a gravitational wave to the vibrations that sound makes).

By the end of 2021, the LIGO-Virgo collaboration (Virgo is a gravitational wave detector operated by the European Gravitational Observatory in Italy) published a catalog that now included some 90 events. Most were mergers of two black holes, and most involved black holes with a range of masses detected only by gravitational waves (see Figure 24.19). In the most extreme merger, black holes with masses of 86 and 65 times the mass of the Sun merged to form a black hole with a mass of about 142 times the mass the Sun, and released energy equivalent to 9 times the mass of our Sun (remember $E= mc^2$)—an enormous amount.

Astronomers are not yet sure how black holes in this unexpected mass range form. Bear in mind that the kind of black holes in binary star systems that we discussed in Evidence for Black Holes (and listed in Table 24.1) have masses ranging from 4 to 15 times the mass of the Sun.

To be sure, a few mergers did involve black holes with stellar masses comparable to those of black holes in X-ray binary systems. In one case, for example, the merging black holes had masses of 14 and 8 times the mass of the Sun.

While astronomers can learn about the masses of objects involved in gravitational wave events, the challenge is to locate the event in the sky precisely. A single gravitational wave detector cannot determine accurately the direction to a gravitational wave source. Four comparable detectors operating simultaneously are required to localize a source of gravitational waves *in every location* in the sky. The first observing run with four detectors, including the two LIGO detectors, Virgo, and KAGRA in Japan, is scheduled to begin in the summer of 2022. LIGO India will be a fifth, thereby enhancing the probability that at least four detectors will be operational simultaneously. Experience has shown that the LIGO and Virgo detectors are down about 25 percent of the time because these complex systems are difficult to run.

A three-observatory network does provide a sharp location for events that occur in about half of all possible locations on the sky.

In late 2017, data from the LIGO and Virgo detectors provided an accurate position for what analysis showed was the spiraling together of two neutron stars with masses of 1.1 to 1.6 times the mass of the Sun (see The Death of Stars).

With an accurate location known, follow up observations with ground-based telescopes detected electromagnetic emission from a gravitational wave event for the first time. The observations showed that this source was located in NGC 4993, a galaxy at a distance of about 130 million light-years in the direction of the constellation Hydra. The Fermi satellite detected a flash of gamma rays at the same time and in the same direction, which confirms the long-standing hypothesis that mergers of neutron stars are progenitors of short gamma-ray bursts (see The Mystery of Gamma-Ray Bursts). Spectra showed that the merger ejected material with a mass of about 6 percent of the mass of the Sun at a speed of one-tenth the speed of light.

This material is rich in heavy elements, just as the theory of kilonovas (see The Mystery of Gamma-Ray Bursts) predicted. First estimates suggest that the merger produced about 200 Earth masses of gold, and around 500 Earth masses of platinum. This makes clear that neutron star mergers are a significant source of heavy elements. More such mergers are being found (see Figure 24.19) and they will improve estimates of the frequency at which neutron star mergers occur; it may well turn out that the vast majority of heavy elements have been created in such cataclysms.

No electromagnetic observations have been detected from the mergers of two black holes.

In June 2021, scientists from LIGO and Virgo announced the first detection of mergers between black holes and neutron stars, another of the really energetic events that we listed as possible sources for a detectable burst of gravitational waves. Again, no electromagnetic waves from the two events were observed or expected, demonstrating the importance of using what we are now calling “multi-messenger astronomy” to understand the universe fully.

Observing the merger of black holes via gravitational waves means that we can now test Einstein’s general theory of relativity where its effects are very strong—close to black holes—and not weak, as they are near Earth. One remarkable result from these detections is that the observed signals so closely match the theoretical predictions made using Einstein’s theory. Once again, Einstein’s revolutionary idea is found to be the correct description of nature.

Because of the scientific significance of the observations of gravitational waves, three of the LIGO project leaders—Rainer Weiss of MIT, and Kip Thorne and Barry Barish of Caltech—were awarded the Nobel Prize in 2017.

Ground-based gravitational-wave detectors can detect mergers of black holes with masses up to about 100 times the mass of the Sun. Astronomers would now like to look for the merger of distant supermassive black holes (see Supermassive Black Holes: What Quasars Really Are) with masses of thousands to millions of times larger, which might have occurred when the first generation of stars formed, only a few hundred million years after the Big Bang. The gravitational waves emitted by mergers of supermassive black holes are so long that it is necessary to go to space to build an observatory large enough to detect them.

ESA (the European Space Agency), with contributions from NASA, is planning to launch a facility named LISA (Laser Interferometer Space Antenna) in 2034 to search for mergers of black holes with masses thousands to millions of times larger than the mass of the Sun. The experiment will consist of three spacecraft arranged in an equilateral triangle with sides 2.5 million km long, flying along an Earth-like heliocentric orbit. A test mass floats free inside each spacecraft, effectively in free-fall, while the spacecraft around it absorbs the effects of light pressure, solar wind particles, and anything that might perturb its orbit. Lasers will be used to measure very accurately the distances between the test masses. Changes in distance will then signal the passing of gravitational waves.

We should end by acknowledging that the ideas discussed in this chapter may seem strange and overwhelming, especially the first time you read them. The consequences of the general theory of relatively take some getting used to. But they make the universe more bizarre—and interesting—than you probably thought before you took this course.

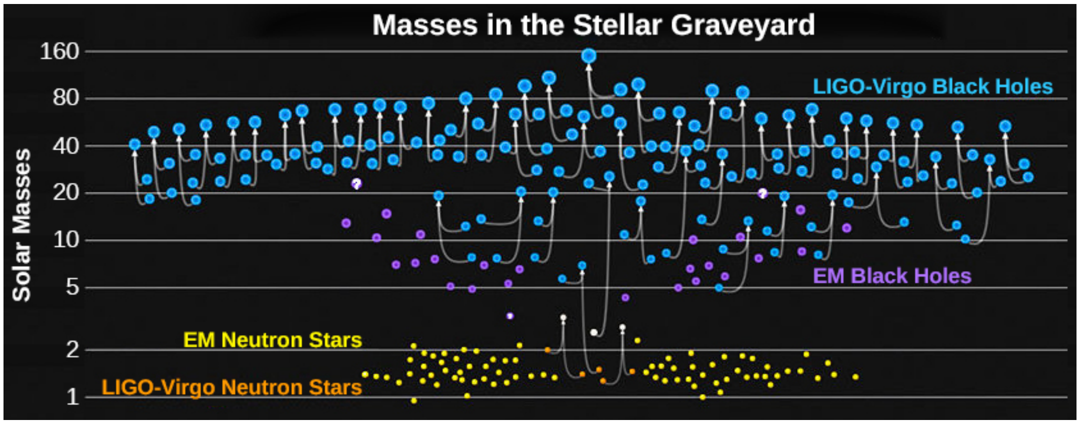


Figure 24.19 Some Black Hole Merger Events Observed with Gravitational Waves. The vertical axis shows the masses for some known black holes and neutron stars. The light blue dots represent black hole mergers seen with LIGO-Virgo, with the individual black holes and the resulting merged black hole connected with an arrow. Note that, as a result of these mergers, we are starting to observe some black holes with masses so large that new ideas may be required to explain them. The purple dots represent black holes seen with electro-magnetic radiation; these have significantly smaller masses. The orange dots represent neutron star mergers seen through the gravitational waves they emit. The yellow dots are neutron stars seen with electro-magnetic radiation. (credit: courtesy Caltech/MIT/LIGO Laboratory; LIGO-Virgo/Frank Elavsky, Aaron Geller/Northwestern)