Feeding a Black Hole

After an isolated star, or even one in a binary star system, becomes a black hole, it probably won't be able to grow much larger. Out in the suburban regions of the Milky Way Galaxy where we live (see **The Milky Way Galaxy**), stars and star systems are much too far apart for other stars to provide "food" to a hungry black hole. After all, material must approach very close to the event horizon before the gravity is any different from that of the star before it became the black hole.

But, as will see, the central regions of galaxies are quite different from their outer parts. Here, stars and raw material can be quite crowded together, and they can interact much more frequently with each other. Therefore, black holes in the centers of galaxies may have a much better opportunity to find mass close enough to their event horizons to pull in. Black holes are not particular about what they "eat": they are happy to consume other stars, asteroids, gas, dust, and even other black holes. (If two black holes merge, you just get a black hole with more mass and a larger event horizon.)

As a result, black holes in crowded regions can grow, eventually swallowing thousands or even millions of times the mass of the Sun. Ground-based observations have provided compelling evidence that there is a black hole in the center of our own Galaxy with a mass of about 4 million times the mass of the Sun (we'll discuss this further in the chapter on **The Milky Way Galaxy**). Observations with the Hubble Space Telescope have shown dramatic evidence for the existence of black holes in the centers of many other galaxies. These black holes can contain more than a billion solar masses. The feeding frenzy of such supermassive black holes may be responsible for some of the most energetic phenomena in the universe (see **Active Galaxies, Quasars, and Supermassive Black Holes**). And evidence from more recent X-ray observations is also starting to indicate the existence of "middle-weight" black holes, whose masses are dozens to thousands of times the mass of the Sun. The crowded inner regions of the globular clusters we described in **Stars from Adolescence to Old Age** may be just the right breeding grounds for such intermediate-mass black holes.

Over the past decades, many observations, especially with the Hubble Space Telescope and with X-ray 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.

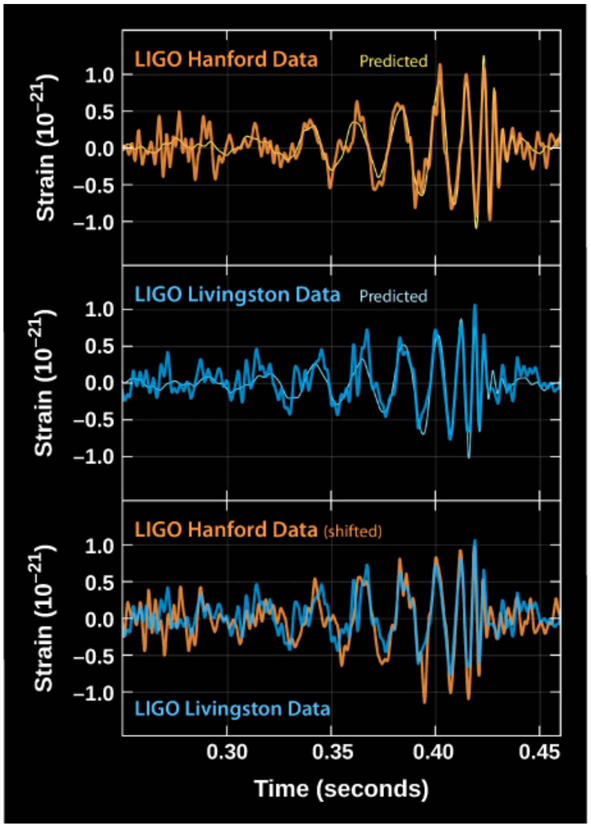
Figure 24.17 Gravitational Wave Telescope. An aerial view of the LIGO facility at Livingston, Louisiana. Extending to the upper left and far right of the image are the 4-kilometer-long detectors. (credit: modification of work by Caltech/MIT/LIGO Laboratory)

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.

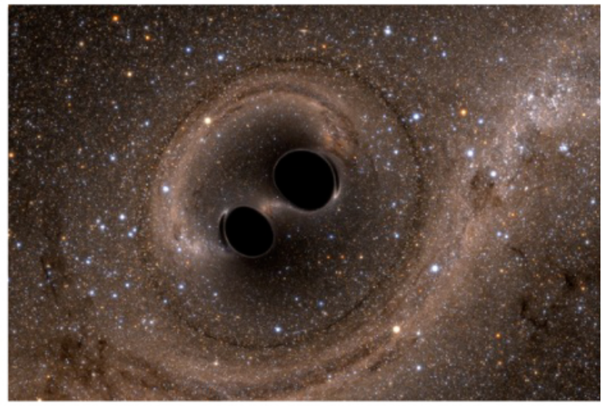
A great deal of new technology had to be developed, and work on the laboratory, with funding from the National Science Foundation, began in 1979. A full-scale prototype to demonstrate the technology was built and operated from 2002 to 2010, but the prototype was not expected to have the sensitivity required 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) opens 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 2017, LIGO had detected four more mergers of black holes. Two of these, like the initial discovery, involved mergers of black holes with a range of masses that have been observed only by gravitational waves. In one merger, black holes with masses of 31 and 25 times the mass of the Sun merged to form a spinning black hole with a mass of about 53 times the mass the Sun. This event was detected not only by the two LIGO detectors, but also by a newly operational European gravitational wave observatory, Virgo. The other event was caused by the merger of 20- and 30-solar-mass black holes, and resulted in a 49-solar-mass black hole. Astronomers are not yet sure just how black holes in this mass range form.

Two other mergers detected by LIGO involved black holes with stellar masses comparable to those of black holes in X-ray binary systems. In one case, the merging black holes had masses of 14 and 8 times the mass of the Sun. The other event, again detected by both LIGO and Virgo, was produced by a merger of black holes with masses of 7 and 12 times the mass of the Sun. None of the mergers of black holes was detected in any other way besides gravitational waves. It is quite likely that the merger of black holes does not produce any electromagnetic radiation.

In late 2017, data from all three gravitational wave observatories was used to locate the position in the sky of a fifth event, which was produced by the merger of objects with masses of 1.1 to 1.6 times the mass of the Sun. This is the mass range for neutron stars (see **The Milky Way Galaxy**), so in this case, what was observed was the spiraling together of two neutron stars. Data obtained from all three observatories enabled scientists to narrow down the area in the sky where the event occurred. The Fermi satellite offered a fourth set of observational data, detecting a flash of gamma rays at the same time, 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**). The *Swift* satellite also detected a flash of ultraviolet light at the same time, and in the same part of the sky. This was the first time that a gravitational wave event had been detected with any kind of electromagnetic wave.

The combined observations from LIGO, Virgo, Fermi, and *Swift* 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. With a well-defined position, ground-based observatories could point their telescopes directly at the source and obtain its spectrum. These observations showed that the merger ejected material with a mass of about 6 percent of the mass of the Sun, and a speed of one-tenth the speed of light. This material is rich in heavy elements, just as the theory of kilonovas (see **Short-Duration Gamma-Ray Bursts: Colliding Stellar Corpses**) 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. As additional detections of such events improve theoretical 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.

The detection of gravitational waves opens a whole new window to 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). We can now learn about events, such as the merger of black holes, that can be studied in no other way.

Observing the merger of black holes via gravitational waves also 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 signals measured 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.

Several facilities similar to LIGO and Virgo are under construction in other countries to contribute to gravitational wave astronomy and help us pinpoint more precisely pinpoint the location of signals we detect in the sky. The European Space Agency (ESA) is exploring the possibility of building an even larger detector for gravitational waves in space. The goal is to launch a facility called eLISA sometime in the mid 2030s. The design calls for three detector arms, each a million kilometers in length, for the laser light to travel in space. This facility could detect the merger of distant supermassive black holes, which might have occurred when the first generation of stars formed only a few hundred million years after the Big Bang.

In December 2015, ESA launched LISA Pathfinder and successfully tested the technology required to hold two gold-platinum cubes in a state of weightless, perfect rest, relative to one another. While LISA Pathfinder cannot detect gravitational waves, such stability is required if eLISA is to be able to detect the small changes in path length produced by passing 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.