such different views of the same event could be correct, each in its own "world," and they tried to find a mistake in the calculations. There were no mistakes: we and the astronaut really would see him fall into a black hole very differently.

For the astronaut, there is no turning back. Once inside the event horizon, the astronaut, along with any signals from his radio transmitter, will remain hidden forever from the universe outside. He will, however, not have a long time (from his perspective) to feel sorry for himself as he approaches the black hole. Suppose he is falling feet first. The force of gravity that the singularity exerts on his feet is greater than on his head, so he will be stretched slightly. Because the singularity is a point, the left side of his body will be pulled slightly toward the right, and the right slightly toward the left, bringing each side closer to the singularity. The astronaut will therefore be slightly squeezed in one direction and stretched in the other. Some scientists like to call this process of stretching and narrowing *spaghettification.* The point at which the astronaut becomes so stretched that he perishes depends on the size of the black hole. For black holes with masses billions of times the mass of the Sun, such as those found at the centers of galaxies, the spaghettification becomes significant only after the astronaut passes through the event horizon. For black holes with masses of a few solar masses, the astronaut will be stretched and ripped apart even before he reaches the event horizon.

Earth exerts similar *tidal forces* on an astronaut performing a spacewalk. In the case of Earth, the tidal forces are so small that they pose no threat to the health and safety of the astronaut. Not so in the case of a black hole. Sooner or later, as the astronaut approaches the black hole, the tidal forces will become so great that the astronaut will be ripped apart, eventually reduced to a collection of individual atoms that will continue their inexorable fall into the singularity.

LINK TO LEARNING

From the previous discussion, you will probably agree that jumping into a black hole is definitely a once-in-a-lifetime experience! You can see an engaging explanation (https://openstax.org/l/30ndegtystidfor) of death by black hole by Neil deGrasse Tyson, where he explains the effect of tidal forces on the human body until it dies by spaghettification.

An overview of black holes is given in this Discovery Channel video (https://openstax.org/l/30dischatidfor) excerpt.

24.6 Evidence for Black Holes

Learning Objectives

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

- Describe what to look for when seeking and confirming the presence of a stellar black hole
- Explain how a black hole is inherently black yet can be associated with luminous matter
- Differentiate between stellar black holes and the black holes in the centers of galaxies

Theory tells us what black holes are like. But do they actually exist? And how do we go about looking for something that is many light years away, only about a few dozen kilometers across (if a stellar black hole), and completely black? It turns out that the trick is not to look for the black hole itself but instead to look for what it does to a nearby companion star.

As we saw, when very massive stars collapse, they leave behind their gravitational influence. What if a member of a double-star system becomes a black hole, and its companion manages to survive the death of the massive star? While the black hole disappears from our view, we may be able to deduce its presence from the things it does to its companion.

Requirements for a Black Hole

So, here is a prescription for finding a black hole: start by looking for a star whose motion (determined from the Doppler shift of its spectral lines) shows it to be a member of a binary star system. If both stars are visible, neither can be a black hole, so focus your attention on just those systems where only one star of the pair is visible, even with our most sensitive telescopes.

Being invisible is not enough, however, because a relatively faint star might be hard to see next to the glare of a brilliant companion or if it is shrouded by dust. And even if the star really is invisible, it could be a neutron star. Therefore, we must also have evidence that the unseen star has a mass too high to be a neutron star and that it is a collapsed object—an extremely small stellar remnant.

We can use Kepler's law (see Orbits and Gravity) and our knowledge of the visible star to measure the mass of the invisible member of the pair. If the mass is greater than about 3 M_{Sun}, then we are likely seeing (or, more precisely, not seeing) a black hole—as long as we can make sure the object really is a collapsed star.

If matter falls toward a compact object of high gravity, the material is accelerated to high speed. Near the event horizon of a black hole, matter is moving at velocities that approach the speed of light. As the atoms whirl chaotically toward the event horizon, they rub against each other; internal friction can heat them to temperatures of 100 million K or more. Such hot matter emits radiation in the form of flickering X-rays. The last part of our prescription, then, is to look for a source of X-rays associated with the binary system. Since X-rays do not penetrate Earth's atmosphere, such sources must be found using X-ray telescopes in space.

In our example, the infalling gas that produces the X-ray emission comes from the black hole's companion star. As we saw in The Death of Stars, stars in close binary systems can exchange mass, especially as one of the members expands into a red giant. Suppose that one star in a double-star system has evolved to a black hole and that the second star begins to expand. If the two stars are not too far apart, the outer layers of the expanding star may reach the point where the black hole exerts more gravitational force on them than do the inner layers of the red giant to which the atmosphere belongs. The outer atmosphere then passes through the point of no return between the stars and falls toward the black hole.

The mutual revolution of the giant star and the black hole causes the material falling toward the black hole to spiral around it rather than flow directly into it. The infalling gas whirls around the black hole in a pancake of matter called an **accretion disk**. It is within the inner part of this disk that matter is revolving about the black hole so fast that internal friction heats it up to X-ray–emitting temperatures (see Figure 24.1).

Another way to form an accretion disk in a binary star system is to have a powerful stellar wind come from the black hole's companion. Such winds are a characteristic of several stages in a star's life. Some of the ejected gas in the wind will then flow close enough to the black hole to be captured by it into the disk (Figure 24.16).

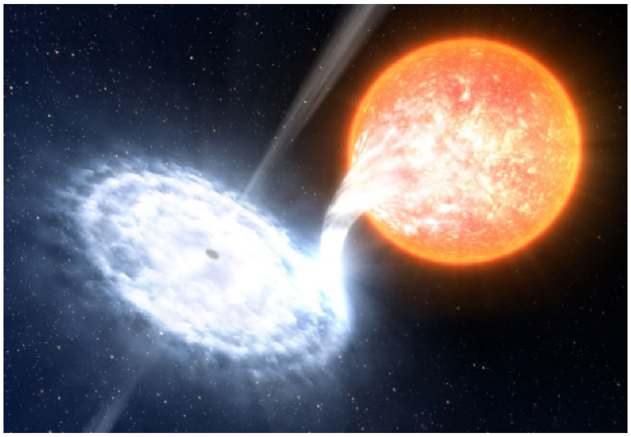

Figure 24.16 Binary Black Hole. This artist's rendition shows a black hole and star (red). As matter streams from the star, it forms a disk around the black hole. Some of the swirling material close to the black hole is pushed outward perpendicular to the disk in two narrow jets. (credit: modification of work by ESO/L. Calçada)

We should point out that, as often happens, the measurements we have been discussing are not quite as simple as they are described in introductory textbooks. In real life, Kepler's law allows us to calculate only the combined mass of the two stars in the binary system. We must learn more about the visible star of the pair and its history to ascertain the distance to the binary pair, the true size of the visible star's orbit, and how the orbit of the two stars is tilted toward Earth, something we can rarely measure. And neutron stars can also have accretion disks that produce X-rays, so astronomers must study the properties of these X-rays carefully when trying to determine what kind of object is at the center of the disk. Nevertheless, a number of systems that clearly contain black holes have now been found.

The Discovery of Stellar-Mass Black Holes

Because X-rays are such important tracers of black holes that are having some of their stellar companions for lunch, the search for black holes had to await the launch of sophisticated X-ray telescopes into space. These instruments must have the resolution to locate the X-ray sources accurately and thereby enable us to match them to the positions of binary star systems.

The first black hole binary system to be discovered is called Cygnus X-1 (see Figure 24.1). The visible star in this binary system is spectral type O. Measurements of the Doppler shifts of the O star's spectral lines show that it has an unseen companion. The X-rays flickering from it strongly indicate that the companion is a small collapsed object. The mass of the invisible collapsed companion is about 15 times that of the Sun. The companion is therefore too massive to be either a white dwarf or a neutron star.

A number of other binary systems also meet all the conditions for containing a black hole. Table 24.1 lists the characteristics of some of the best examples.

Some Black Hole Candidates in Binary Star Systems

Name/Catalog Designation[2]	Companion Star Spectral Type	Orbital Period (days)	Black Hole Mass Estimates (M_{Sun})
LMC X-1	O giant	3.9	10.9
Cygnus X-1	O supergiant	5.6	15
XTE J1819.3-254 (V4641 Sgr)	B giant	2.8	6–7
LMC X-3	B main sequence	1.7	7
4U1543-475 (IL Lup)	A main sequence	1.1	9
GRO J1655-40 (V1033 Sco)	F subgiant	2.6	7
GRS 1915+105	K giant	33.5	14
GS202+1338 (V404 Cyg)	K giant	6.5	12
XTE J1550-564	K giant	1.5	11
A0620-00 (V616 Mon)	K main sequence	0.33	9–13

Table 24.1

Name/Catalog Designation[2]	Companion Star Spectral Type	Orbital Period (days)	Black Hole Mass Estimates (M_{Sun})
H1705-250 (Nova Oph 1977)	K main sequence	0.52	5–7
GRS1124-683 (Nova Mus 1991)	K main sequence	0.43	7
GS2000+25 (QZ Vul)	K main sequence	0.35	5–10
GRS1009-45 (Nova Vel 1993)	K dwarf	0.29	8–9
XTE J1118+480	K dwarf	0.17	7
XTE J1859+226	K dwarf	0.38	5.4
GRO J0422+32	M dwarf	0.21	4

Table 24.1

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

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[2] As you can tell, there is no standard way of naming these candidates. The chain of numbers is the location of the source in right ascension and declination (the longitude and latitude system of the sky); some of the letters preceding the numbers refer to objects (e.g., LMC) and constellations (e.g., Cygnus), while other letters refer to the satellite that discovered the candidate—A for Ariel, G for Ginga, and so on. The notations in parentheses are those used by astronomers who study binary star system or novae.

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.