The "Sounds" of Black Holes

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Black holes may seem like mysterious objects from science fiction, but observational evidence suggests that they are, in fact, quite common. Supermassive black holes, of masses 100,000 to 10,000,00 times that of our Sun, are believed to lie at the heart of every galaxy. Additionally, there are several smaller black holes, of masses roughly 3 to 200 times that of the Sun, strewn throughout every galaxy. Current estimates suggest that there are upward of 10^{19} black holes in the universe (Sicili et al., 2022).

The defining feature of a black hole is its event horizon, a region from which nothing can escape, not even light. On the face of it, this would seem to make observing black holes difficult. Evidence of black holes thus relies on observing the effects that they have on things, like stars and gas, around them. Moreover, black holes have been found to cause wave-related phenomena: frequency shifting of light, reverberation of sounds (which constitute the lowest known notes produced in the universe) through their surrounding medium, and even ripples throughout space and time.

Gravity and Black Holes

Black holes as a concept seem far removed from us here on Earth. To truly understand black holes, we must first understand gravity. As residents of Earth and popular science consumers, we are all, intuitively, aware of gravity.

Newtonian Gravity

Most of us internalize this notion of gravity along the following lines: the more massive an object is, the harder you are pulled toward it, and the closer you are to a massive object, the harder you are pulled toward it. Our intuitive understanding is usually aligned with the description of gravity laid out by Isaac Newton (1687). Newton's universal law of gravitation states that the force between two objects is proportional to the masses of the objects and inversely related to the square of the distance between the objects. This conception of gravity describes why planets travel in elliptical orbits around the Sun, explains why you can jump higher and fall slower on the moon than on Earth, and tells us how fast we need to propel rockets to launch them into space.

Launching rockets into space from Earth's surface requires consideration of the escape velocity. Escape velocity, which can be derived from Newton's law of gravitation, is the velocity with which an object on the surface of a massive body, like a planet, must be launched to "escape" the gravity of the massive body. If launched with a speed less than the escape velocity, the object eventually slows to a stop and falls back to the surface. Escape velocity depends crucially on the ratio of the body's mass and radius.

Newtonian gravity (and escape velocity therein) seeded the first conception of what we would now call a black hole. In 1783, philosopher John Michell posited the existence of "dark stars," bodies so massive that their escape velocities were the speed of light. Today, this idea of a body from which objects cannot escape sounds remarkably like a black hole. The radius from which the escape velocity is the speed of light marks the black hole's defining feature, the event horizon (Michell, 1784).

Newtonian gravity provides a reasonable description for most of our everyday life and was accurate enough to take us to the moon during the 1969 Apollo 11 mission. But even in 1969, Newtonian gravity was known to be only an approximate description of how gravity works in our universe. Indeed, in 1915, Albert Einstein wrote a more precise description of gravity called the general theory of relativity (colloquially known as general relativity or Einstein gravity) (Einstein, 1916).

Einstein Gravity: General Relativity

Understanding the theory of general relativity demands we radically shift our way of thinking about gravity. Where Newtonian gravity tells us that gravity is a force of attraction felt by objects due to mass, Einstein's

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equations for gravity directly relate the geometric shape of space-time to the distribution of matter and energy in the space-time. Heuristically, general relativity says, in the words of physicist John A. Wheeler, "space-time tells matter how to move; matter tells space-time how to curve" (Wheeler and Ford, 1998).

The concept of "space-time" was seeded in Einstein's 1905 theory of special relativity (Einstein, 1905). The defining feature of special relativity is that everyone measures the speed of light to be 2.998×10^8 meters/second. Special relativity implies that what we perceive as the three-dimensional (3D) space and the passage of time are all part of a four-dimensional geometric object called "space-time" (Minkowski, 1908). Special relativity does not include gravity and is only a good approximation when masses are sufficiently small so as not to cause large amounts of curvature in space-time.

Evidence in support of Einstein gravity over Newtonian gravity was immediately available because Einstein showed that general relativity solved a long-standing problem of explaining the orbit of Mercury around the Sun (Einstein, 1916). Another test Einstein proposed to determine whether general relativity better models nature than Newtonian gravity was gravitational lensing. Gravitational lensing is the deflection of light around massive bodies and is so named because massive objects cause light to travel on bent paths in a manner similar to light through an optical lens. Measurements made of the 1919 total solar eclipse supported Einstein gravity (Dyson et al., 1920; Gates and Pelletier, 2019).

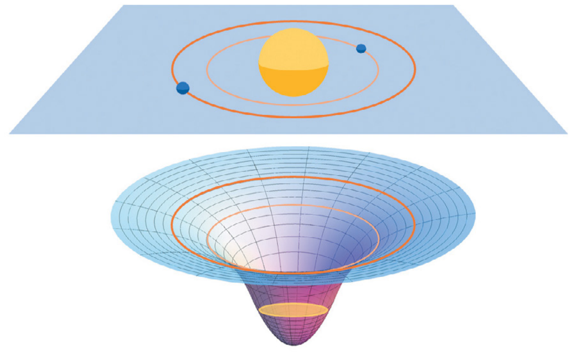
When Einstein wrote his theory of gravity, he never expected anyone to be able to come up with a solution for a space-time shape that would exactly satisfy his equations. But, rather quickly, Schwarzschild (1916) calculated the solution describing the space-time around a nonrotating mass. Unknown to Einstein, Schwarzchild had studied the mathematics of curved three-dimensional space, although not four-dimensional space-time, a decade earlier. The Schwarzschild solution held a remarkable feature: the possibility of a black hole! In the Schwarzschild solution, there is a critical radius, now called the Schwarzschild radius. One can think of this critical radius as a one-way door. Objects can travel from the region outside the critical radius to the region inside the critical radius. However, once inside, objects can never travel back out. Thus, if the mass is compact enough to fit inside the Schwarzschild radius, this radius marks the event horizon of a black hole!

Although the possibility of black holes was once again mathematically realized in general relativity, just as the dark stars were in Newtonian gravity, Einstein himself was skeptical of their existence. Interpretation of the Schwarzschild solution (1916) was a topic of great debate among Einstein and his contemporaries. It remained an open question whether the matter in our universe was compressible enough to achieve the densities needed to create black holes. Excitingly, the matter in our universe does seem to allow for black holes, and we now live in a time where astronomical observational technology has allowed us to push the existence of black holes from scientific speculation to scientific fact.

Visualizing Space-Time Curvature

To understand observational evidence of black holes, imagining what is meant by "the curvature of space-time" is beneficial. When trying to visualize the space-time curvature, images like those in **Figure 1** are often shown. While instructive, their interpretation can be subtle. If we consider small objects moving in a plane around a more massive body, the objects appear to move on curved paths around the massive body (**Figure 1**, *top*). In actuality, the plane to which motion is confined has a curvature

Figure 1. *Gravitational potential.* ***Top:*** *motion of small objects (**blue**) traveling in a plane around a massive body (**yellow**). The orbits of the objects are shown in **orange** and **pink**.* ***Bottom:*** *gravitational potential is shown as a basin. The motions of objects in the plane are a projection of their motions along the surface of the potential. See text for detailed explanation.*



that can be analogized to the two-dimensional surface of, say, a basin (**Figure 1**, *bottom*).

The depth of the basin represents the "gravitational potential" and is set by the mass of the central body. When there is no massive body, objects move in the plane as expected; however, when a massive body curves the space-time, objects move similarly to marbles along the surface of the basin.

In the basin analogy, we can imagine a marble on a myriad of orbits: closed orbits like elliptical or circular orbits; hyperbolic orbits that start far from the central mass, approach it, then zoom back out; and orbits that spiral in/out of the basin. We can visualize the change in speed that objects experience along their orbits, increasing and decreasing as they approach or move away from the basin center. We can also imagine escape velocity: how hard must we flick a marble in the well of the basin for it to climb out entirely and not eventually slow to a stop before turning around and falling back toward the center? Light also moves along this curved space in similar ways; however, its speed is always constant.

Observing Black Holes with Waves

Several observational signatures of black holes are related to wave phenomena. These signatures make use of three types of waves: electromagnetic waves, pressure waves, and gravitational waves.

Electromagnetic Waves

It may come as no surprise that electromagnetic wave (light) observations are a common way to gather evidence of black holes because most astronomical objects are identified with telescopes. Tracking the motion of stars in our own galactic center has allowed us to locate and measure the mass of the supermassive black hole central to the Milky Way, earning the scientists who led these efforts a Nobel Prize in 2020 (see tinyurl.com/galactic-center-star-orbits) (Ghez et al, 2008; Abuter et al., 2022). The black hole is named Sagittarius A* (Sgr A*). Additionally, the first images of the extreme lensing of light around black holes on the scale of a few Schwarzschild radii have been produced by the Event Horizon Telescope (see eventhorizontelescope.org). The first of these images, made in 2017, showcases a behemoth of a supermassive black hole named M87* that lives at the center of the Messier 87 (M87) galaxy (see tinyurl.com/eht-m87); the second image is that of Sgr A* released in 2022 (see tinyurl.com/eht-sgra) (Akiyama et al., 2019 , 2022). But both these methods of black hole observations are narrowly applicable with current technology. Observations that make use of the wavelike nature of light can be applied more widely.

Electromagnetic radiation is composed of transverse waves of the electric and magnetic fields; that is to say, the direction of travel is perpendicular to the direction in which electric and magnetic fields vary. The frequency of an electromagnetic wave is proportional to its energy and, for visible light, is related to its color. Short wavelength/higher frequency light appears bluer, whereas longer wavelength/lower frequency light appears redder. Like sound waves, electromagnetic waves can be Doppler shifted by the motion of the light source relative to the observer. Imagine that I am standing still, shining a laser at you, and you note the color of the light. If I shine the same laser while moving away from you, the light will appear redder. Similarly, the light will appear bluer if I move toward you. This is called relativistic Doppler shifting and is a consequence of special relativity.

Within general relativity, Einstein established a concept called the equivalence principle, which says one cannot distinguish between feeling gravity or standing on an object that is accelerating. It is taught in physics class that the acceleration of gravity felt on Earth (at its surface) is $g = 9.8$ meters/second^2. If blindfolded, you would not be able to distinguish between the feelings of standing on the surface of the earth and of being pushed against a spaceship accelerating through space at g. Unless you have a window to look out of, you cannot make the distinction. (This is the rationale behind creating artificial gravity with spinning space stations like those seen in *2001: A Space Odyssey*, *Interstellar,* and *The Martian*.)

The equivalence principle gives rise to gravitational redshift, which says that the light gets frequency shifted as it climbs into or out of a gravitational potential, just as it would be if emitted by a source moving toward or away from you (Einstein, 1916). Returning to our basin analogy, marbles (massive objects) lose energy as they move away from the steeper center of the basin toward the shallower edges, decreasing in speed, and increase in speed, gaining energy, as they fall into the basin. So, too, does light experience energy shifts as it climbs into or out of a gravitational well; however, the speed of light is constant, so the change in energy is manifested as a shift in frequency.

Today, gravitational redshift has been measured for thousands of galaxy clusters by comparing the frequency of light at the edges of the clusters with the centers where the gravity is stronger (Wojtak et al., 2011). Gravitational redshift has also been measured for our own galactic center by tracking the frequency of light from one of the stars orbiting close to Sgr A* (Abuter et al., 2018).

In some cases, gravitational redshift has been used to measure the rotation rate of black holes. Black holes can rotate like stars and planets. For a nonrotating black hole, the event horizon is at the Schwarzschild radius (1916). But as the rotation rate of the black hole increases, the event horizon gets more compact, shrinking the radius. Therefore, light can be emitted from deeper inside the gravitational potential created by a more rapidly rotating black hole and must incur an even greater redshift to reach an observer far from the black hole like us (Reynolds, 2019).

Acoustic/Pressure Waves

You may have heard "there is no sound in space." This adage arises because most of space is a vacuum where particles are too dilute to constitute a fluid that can support an acoustic wave. Galaxies, which host supermassive black holes, and galaxy clusters can be surrounded by significant amounts of gas that can support sound. Indeed, black holes can churn the gaseous medium and cause compression waves. Although we cannot hear sound waves in the gas around black holes, here on Earth, we can image the medium that supports such waves if the gas is hot and gives off light.

The Perseus cluster is a large galaxy cluster that hosts thousands of galaxies enveloped in extremely hot gas. Pressure waves in the Perseus cluster (see www.nasa.gov/chandra/multimedia/perseus-cluster.html) were discovered by imaging the intracluster gas that glows in the X-ray band of the electromagnetic spectrum using the Chandra X-ray Observatory (see chandra.harvard.edu). The image shows a pattern of over- and underdensities that constitutes a compression wave with a period almost 10^7 years long. This translates to the note B flat 57 octaves under middle C. For comparison, the lowest period humans can here is about 0.05 s (or the frequency of 20 Hz) (see chandra.harvard.edu/photo/2003/perseus) (Fabian et al., 2003).

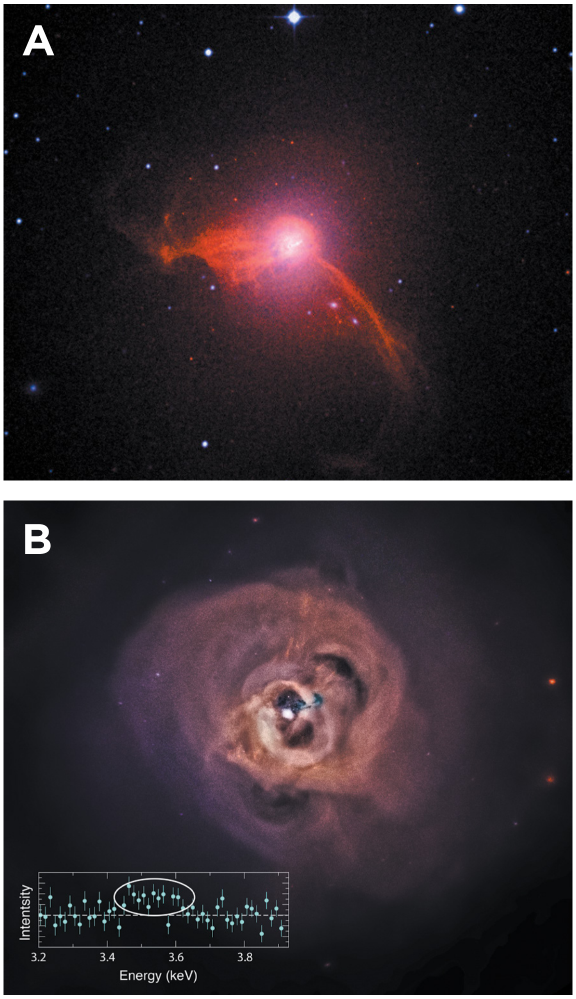


Figure 2. *The Perseus galaxy cluster and the elliptical galaxy M87* ***Top:*** *image of Perseus cluster (see www.nasa.gov/chandra/multimedia/perseus-cluster.html or chandra.harvard.edu/photo/2014/perseus) created using data taken by NASA's Chandra X-ray Observatory. Image credit: X-ray: NASA/CXC/SAO/E. (Bulbul et al., 2014).* ***Bottom:*** *image of M87 galaxy (see chandra.harvard.edu/photo/2006/m87) seen in both X-ray (**red**) and optical (**blue**) spectra. Image from X-ray: NASA/CXC/CfA/W (Forman et al., 2007). Optical: DSS, 2006. Both images were constructed from data taken by NASA's Chandra X-ray Observatory (see chandra.harvard.edu/photo/image_use.html).*

Evidence of black hole sounds has also been detected in the gaseous environment of M87 in the Virgo cluster, again using Chandra. Two different types of structures (bubbles and shocks), suggesting sound waves, were identified. The size of these image features suggests that M87* is creating notes 56 octaves below middle C and, even deeper still, notes at 58 to 59 octaves below middle C. These are the deepest known sounds in the universe (see chandra.harvard.edu/photo/2006/m87) (**Figure 2**) (Forman et al., 2007).

As an aside, there are "sonified" astronomical images by NASA (see chandra.si.edu/sound), including the image of the pressure wave in Perseus cluster. The Perseus sonification is not a simple frequency-shifted version of the notes one would hear ringing out in Perseus if they were to stand still and let the waves pass over them. Instead, these images are translations of the features of the image along radial slices converted into sound in the human hearing range. This kind of sonification can be performed on any image and is an interesting way to experience the data.

Gravitational Waves

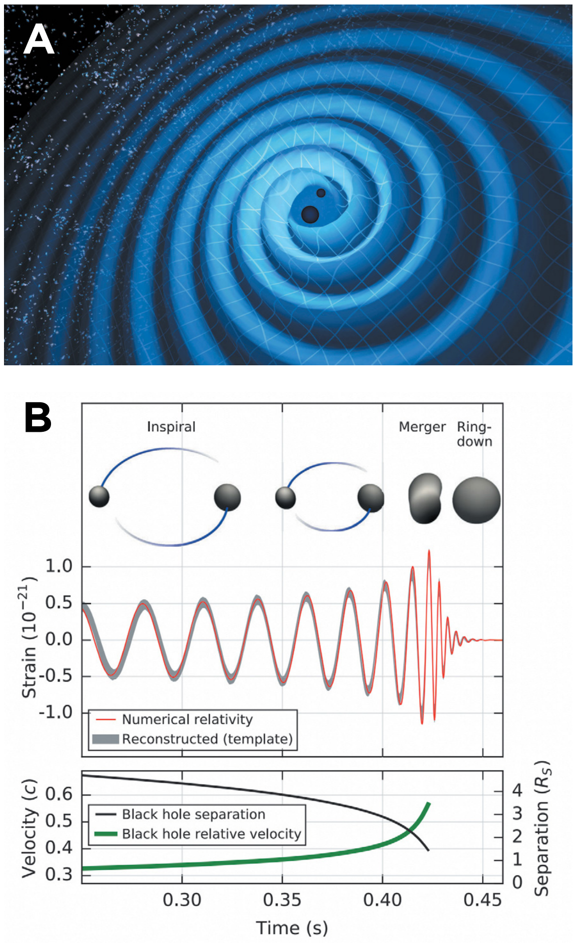
Although light has long been our "messenger" from the heavens giving us information about the wondrous astronomical bodies in the sky, general relativity opened the door for yet another way to detect objects in space: gravitational waves.

Gravitational waves are another prediction of general relativity described by Einstein (1918). Because general relativity describes space-time as a dynamical object that curves in response to the position of matter, it is naturally implied that moving masses should cause waves to ripple through the surface that is space-time, much like moving objects causing waves in water. Gravitational waves propagate at the speed of light and are transverse waves causing space to stretch and contract in the direction perpendicular to their direction of travel.

The gravitational waves caused by most objects are too weak to be detected, so only the most rapidly moving, strongest gravity objects can produce measurable disturbances. But such events do exist in our universe, one example being the merger of binary black holes.

Two black holes can get caught in each other's gravitational potentials, forming a binary. If they are close enough to one another, the black holes will spiral in on each other, gaining speed as their orbital period and the distance between them shrinks, giving off gravitational waves of increasing frequency and amplitude. When the black holes get close enough, they merge into a single black hole, which continues to give off gravitational waves as it vibrates, ringing as it settles down into a stationary state, much like a struck bell producing sound waves (**Figure 3**).

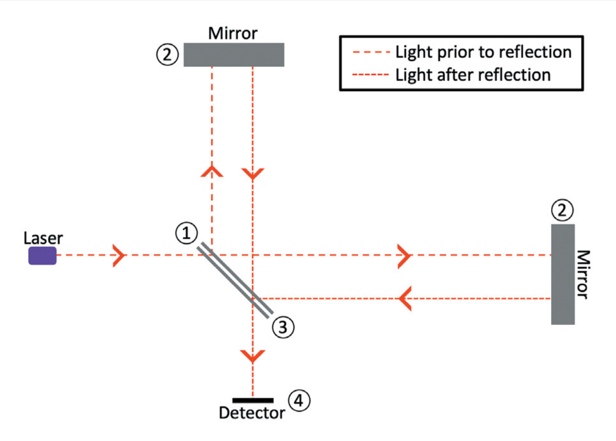
Figure 3. *Gravitational wave from a binary black hole system.* ***Top:*** *illustration of the gravitational waves emanating from binary black holes. Image credit: LIGO/T. Pyle, 2016.* ***Bottom:*** *detection of GW170817 in one of LIGO's detectors. The image shows the strain measured in the detector as the binary black holes go through inspiral (spiraling in on one other getting closer together), merger (where they combine into a single black hole), and ringdown (where the final black hole settles down). The separation and relative velocity of the binary black hole is also shown. Reproduced from Abbott et al. (2016, with permission of the American Physical Society.*



Even the gravitational waves from these violent mergers are extremely weak and measuring them is no easy feat. Still, black hole mergers happen frequently, and we humans on Earth never feel the effects of the passing gravitational waves. But just as small earthquakes unnoticed by humans are measured by seismometers, so too can the weak gravitational waves be detected by observatories like LIGO (see www.ligo.caltech.edu), Virgo (see www.virgo-gw.eu), and KAGRA (see gwcenter.icrr.u-tokyo.ac.jp).

The detectors of the gravitational wave observatories consist of L-shaped interferometers with kilometers-long arms. Laser light travels down the arms, hits a mirror, and travels back. The equipment is carefully stabilized and cooled so the mirrors are very still. When a gravitational wave passes the detectors, stretching or shrinking space, the mirrors move. Thus, the mirrors act like the eardrums of an animal being vibrated by a sound wave, allowing the detector to "hear" the gravitational wave. Motion in the mirrors changes the distance the light travels, which can be measured using changes in the interference pattern (**Figure 4**). LIGO can detect motion in its mirrors with a precision of one ten-thousandth the charge diameter of a proton.

Figure 4. *A simplified schematic of a laser interferometer. A laser is split in two by a half-silvered mirror; (**1**) the beams travel down the arms and encounter mirrors; (**2**) the reflected beams travel back along the arms and are recombined by the half-silvered mirror (**3**); and the recombined beam is shone on a detector (**4**). On recombination, the two beams will interfere. As the length of the arms change, the interference pattern changes.*



The first binary black hole merger detection (called GW150914) was made in 2015 (Abbott et al., 2016). Since the first gravitational wave detection, many more merger events have been found, including mergers whose initial constituents are neutron stars. Neutron stars are the most compact objects in the universe besides black holes. Binary neutron stars, which also result in black holes after merger, produce gravitational wave signals that the gravitational wave interferometers can detect. Observatories can discern between the different merger scenarios based on the waveform from the merger. The first binary neutron star merger detection in gravitational waves (GW170817) was in 2017 (Abbott et al., 2017a). The merger waveforms translated into sound are often called "chirps" because of their characteristic sound as they increase in frequency (see www.ligo.caltech.edu/video/ligo20160615v2)

Light from the first binary neutron star merger event was also seen in a telescope as a gamma ray burst (GRB170817A), marking the dawn of a new era of "multimessenger" astronomy (Abbott et al., 2017b). With ever-increasing advances in telescopes and gravitational wave detectors, including proposals for new larger ground-based detectors (see cosmicexplorer.org; www.et-gw.eu) and a space-based detector (see lisa.nasa.gov), the future of observational black hole astrophysics is both bright and loud.

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