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ASTRONOMY

Chapter 24 BLACK HOLES AND CURVED SPACETIME

PowerPoint Image Slideshow

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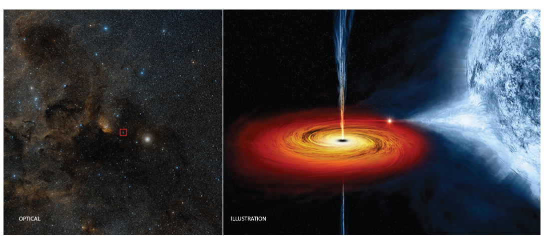
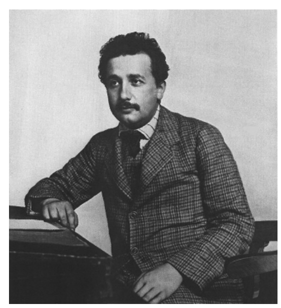
Figure 24.1



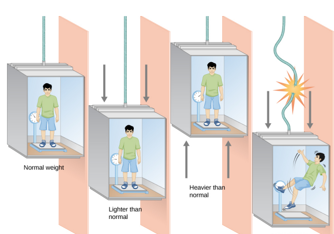
- **Stellar Mass Black Hole.** On the left, a visible-light image shows a region of the sky in the constellation of Cygnus; the red box marks the position of the X-ray source Cygnus X-1. It is an example of a black hole created when a massive star collapses at the end of its life. Cygnus X-1 is in a binary star system, and the artist's illustration on the right shows the black hole pulling material away from a massive blue companion star. This material forms a disk (shown in red and orange) that rotates around the black hole before falling into it or being redirected away from the black hole in the form of powerful jets. The material in the disk (before it falls into the black hole) is so hot that it glows with X-rays, explaining why this object is an X-ray source. (credit left: modification of work by DSS; credit right: modification of work by NASA/CXC/M.Weiss)

24.1 INTRODUCING GENERAL RELATIVITY



- **Albert Einstein (1879–1955).** This famous scientist, seen here younger than in the usual photos, has become a symbol for high intellect in popular culture. (credit: NASA)
- To date, our best theory of gravity is the **general theory of relativity**, which was put forward in 1916 by Albert Einstein.

Figure 24.3



- **Your Weight in an Elevator.** In an elevator at rest, you feel your normal weight. In an elevator that accelerates as it descends, you would feel lighter than normal. In an elevator that accelerates as it ascends, you would feel heavier than normal. If an evil villain cut the elevator cable, you would feel weightless as you fell to your doom.

Figure 24.4

- **Free Fall.** Two people play catch as they descend into a bottomless abyss. Since the people and ball all fall at the same speed, it appears to them that they can play catch by throwing the ball in a straight line between them. Within their frame of reference, there appears to be no gravity.
- This idea that free fall is indistinguishable from, and hence equivalent to, zero gravity is called the **equivalence principle**.

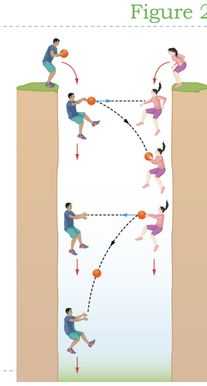
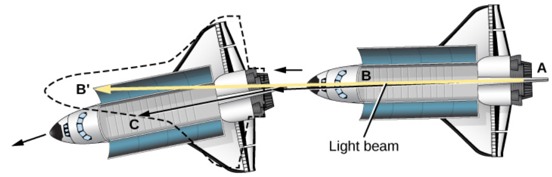


Figure 24.5

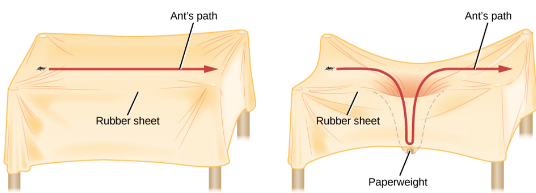
- **Astronauts aboard the Space Shuttle.** Shane Kimbrough and Sandra Magnus are shown aboard the Endeavour in 2008 with various fruit floating freely. Because the shuttle is in free fall as it orbits Earth, everything—including astronauts—stays put or moves uniformly relative to the walls of the spacecraft. This free-falling state produces a lack of apparent gravity inside the spacecraft. (credit: NASA)

24.2 SPACETIME AND GRAVITY



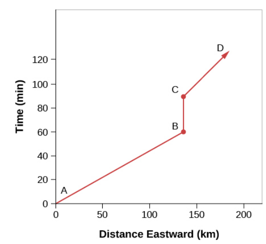
- **Curved Light Path.** In a spaceship moving to the left (in this figure) in its orbit about a planet, light is beamed from the rear, A, toward the front, B. Meanwhile, the ship is falling out of its straight path (exaggerated here). We might therefore expect the light to strike at B′, above the target in the ship. Instead, the light follows a curved path and strikes at C. In order for the principle of equivalence to be correct, gravity must be able to curve the path of a light beam just as it curves the path of the spaceship.

Figure 24.8



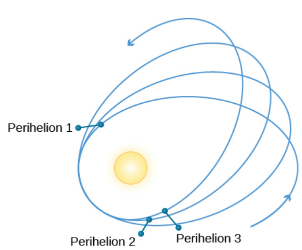
- **Three-Dimensional Analogy for Spacetime.** On a flat rubber sheet, a trained ant has no trouble walking in a straight line. When a massive object creates a big depression in the sheet, the ant, which must walk where the sheet takes it, finds its path changed (warped) dramatically.

24.3 TESTS OF GENERAL RELATIVITY

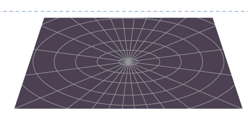


- **Spacetime Diagram.** This diagram shows the progress of a motorist traveling east across the flat Kansas landscape. Distance traveled is plotted along the horizontal axis. The time elapsed since the motorist left the starting point is plotted along the vertical axis.

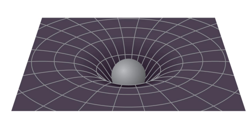
Figure 24.9



- **Mercury's Wobble.** The major axis of the orbit of a planet, such as Mercury, rotates in space slightly because of various perturbations. In Mercury's case, the amount of rotation (or orbital precession) is a bit larger than can be accounted for by the gravitational forces exerted by other planets; this difference is precisely explained by the general theory of relativity. Mercury, being the planet closest to the Sun, has its orbit most affected by the warping of spacetime near the Sun. The change from orbit to orbit has been significantly exaggerated on this diagram.

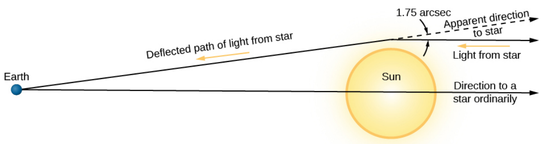


a A two-dimensional representation of "flat" spacetime. The distances between adjacent circles are the same.



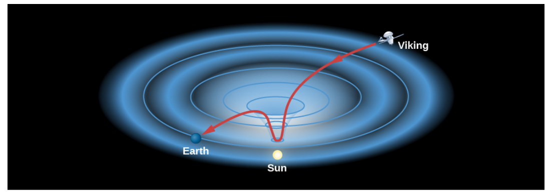
b Gravity arises from curvature of spacetime, represented here by a mass pushing down on the rubber sheet. Notice how the circles become more widely separated near the mass, showing that the curvature is greater as we approach the mass on the sheet.

Figure 24.10

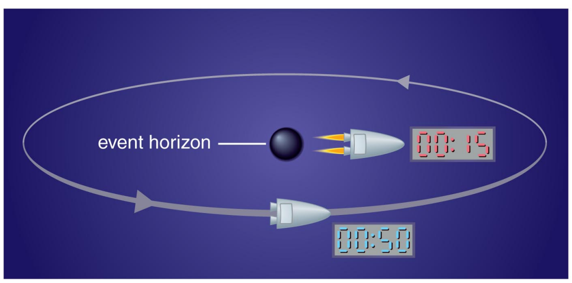


- **Curvature of Light Paths near the Sun.** Starlight passing near the Sun is deflected slightly by the "warping" of spacetime. (This deflection of starlight is one small example of a phenomenon called gravitational lensing, which we'll discuss in more detail in **The Evolution and Distribution of Galaxies**.) Before passing by the Sun, the light from the star was traveling parallel to the bottom edge of the figure. When it passed near the Sun, the path was altered slightly. When we see the light, we assume the light beam has been traveling in a straight path throughout its journey, and so we measure the position of the star to be slightly different from its true position. If we were to observe the star at another time, when the Sun is not in the way, we would measure its true position.

24.4 TIME IN GENERAL RELATIVITY

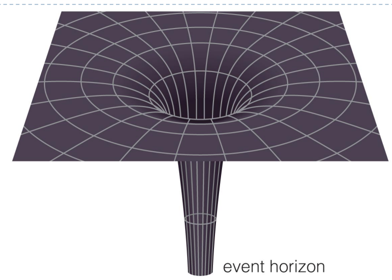


- **Time Delays for Radio Waves near the Sun.** Radio signals from the Viking lander on Mars were delayed when they passed near the Sun, where spacetime is curved relatively strongly. In this picture, spacetime is pictured as a two-dimensional rubber sheet.



Light waves take extra time to climb out of a deep hole in spacetime, leading to a ***gravitational redshift.***
Time passes more slowly near the event horizon.

24.5 BLACK HOLES



c The curvature of spacetime becomes greater and greater as we approach a black hole, and a black hole itself is a bottomless pit in spacetime.

What is a black hole?

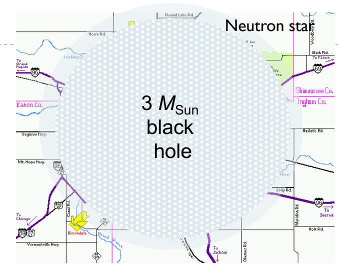
- A ***black hole*** is an object whose gravity is so powerful that not even light can escape it.
- Some massive star supernovae can make a black hole if enough mass falls onto the core.

No Escape

- Nothing can escape from within the event horizon because nothing can go faster than light.
- No escape means there is no more contact with something that falls in. It increases the hole's mass, changes its spin or charge, but otherwise loses its identity.

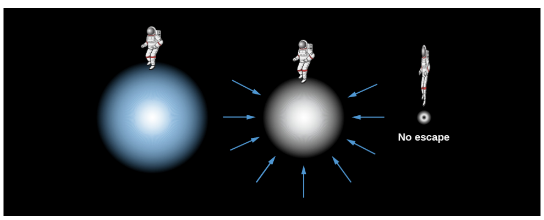
Singularity

- Beyond the neutron star limit, no known force can resist the crush of gravity.
- As far as we know, gravity crushes all the matter into a single point known as a ***singularity.***



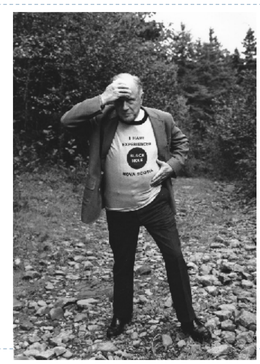
The event horizon of a $3M_{Sun}$ black hole is also about as big as a small city.

Collapse with Relativity



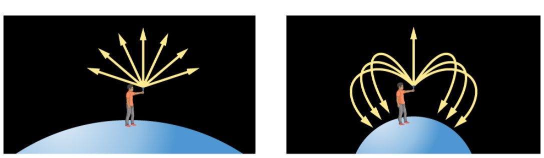
- **Formation of a Black Hole.** At left, an imaginary astronaut floats near the surface of a massive star-core about to collapse. As the same mass falls into a smaller sphere, the gravity at its surface goes up, making it harder for anything to escape from the stellar surface. Eventually the mass collapses into so small a sphere that the escape velocity exceeds the speed of light and nothing can get away. Note that the size of the astronaut has been exaggerated. In the last picture, the astronaut is just outside the sphere we will call the event horizon and is stretched and squeezed by the strong gravity.

Figure 24.13



- **John Wheeler (1911–2008).** This brilliant physicist did much pioneering work in general relativity theory and popularized the term *black hole* starting in the late 1960s. (credit: modification of work by Roy Bishop)

Figure 24.14

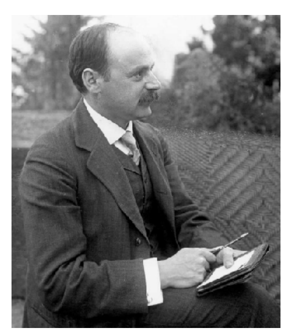


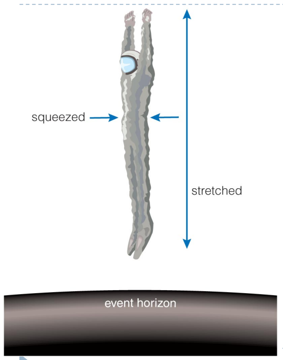
(a) (b)

- **Light Paths near a Massive Object.** Suppose a person could stand on the surface of a normal star with a flashlight. The light leaving the flashlight travels in a straight line no matter where the flashlight is pointed. Now consider what happens if the star collapses so that it is just a little larger than a black hole. All the light paths, except the one straight up, curve back to the surface. When the star shrinks inside the event horizon and becomes a black hole, even a beam directed straight up returns.

Figure 24.15

- **Karl Schwarzschild (1873–1916).** This German scientist was the first to demonstrate mathematically that a black hole is possible and to determine the size of a nonrotating black hole's event horizon.





Tidal forces near the event horizon of a $3M_{Sun}$ black hole would be lethal to humans.

Tidal forces would be gentler near a supermassive black hole because its radius is much bigger.

Figure 24.16

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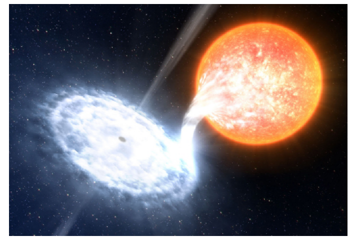
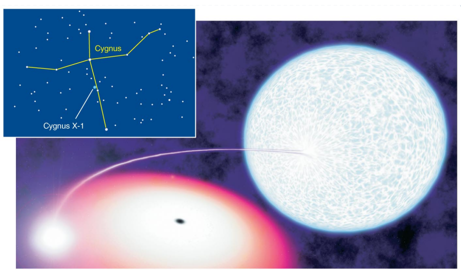


- **Binary Black Hole.** This artist's rendition shows a black hole and star (red). As matter streams from the star, it forms a disk around the black hole. Some of the swirling material close to the black hole is pushed outward perpendicular to the disk in two narrow jets. (credit: modification of work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

24.6 & 24.7 EVIDENCE FOR BLACK HOLES



One famous X-ray binary with a likely black hole is in the constellation Cygnus.

Figure 24.17

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- **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)

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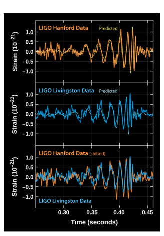
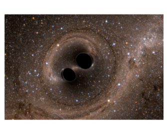


(a)



(b)

- **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)

Links

Reading

- 24.1 optional
- 24.2
- 24.3 optional
- 24.4
- 24.5
- 24.6
- 24.7