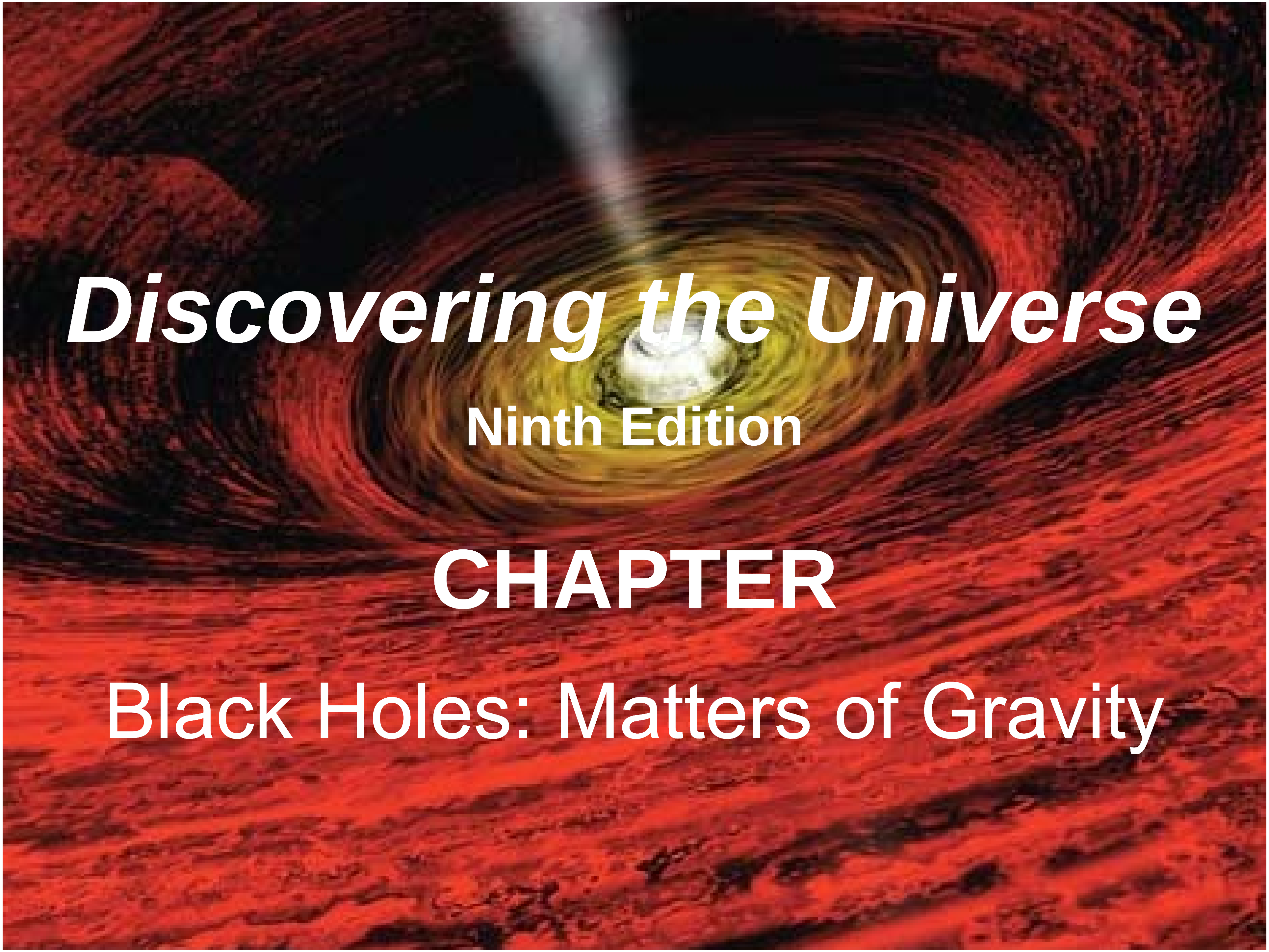

Discovering the Universe
Ninth Edition
CHAPTER
Black Holes: Matters of Gravity

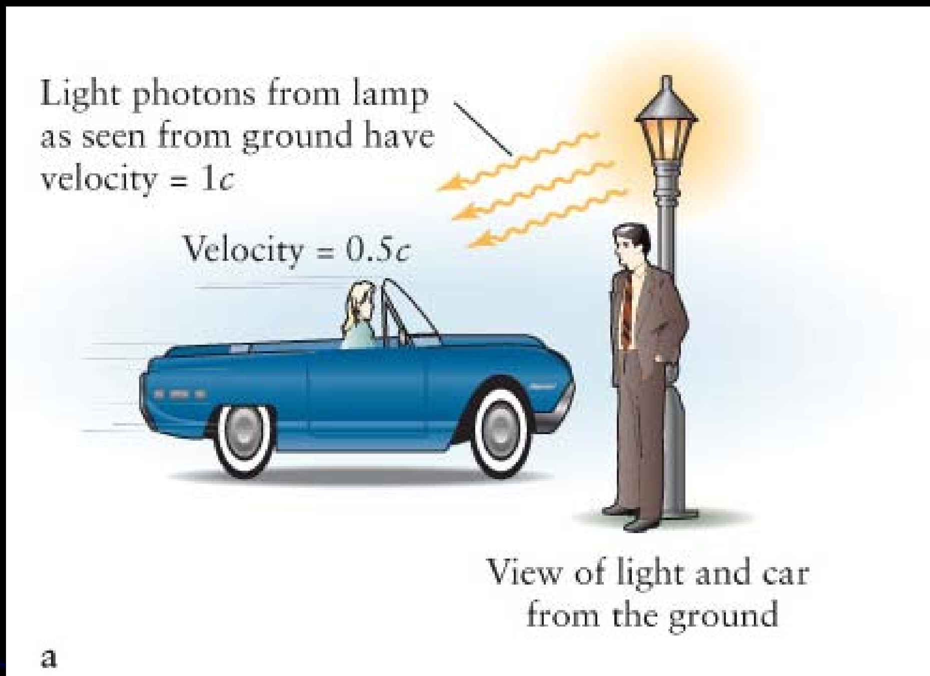
WHAT DO YOU THINK?

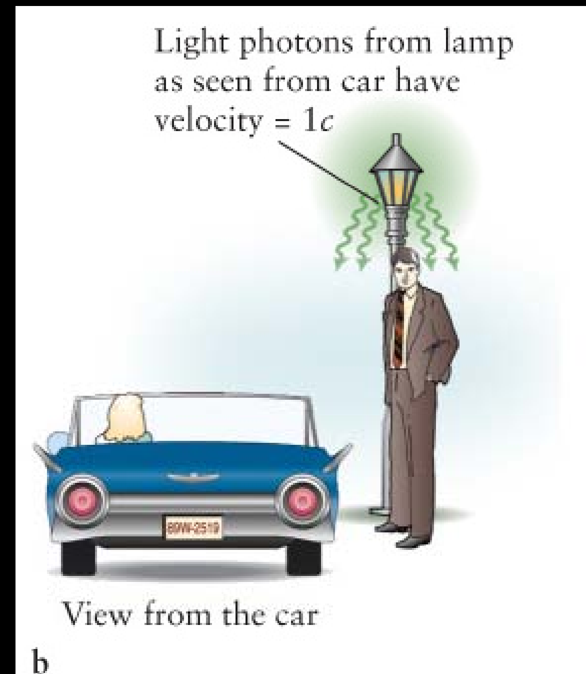
1. Are black holes empty holes in space? If not, what are they?
2. Does a black hole have a solid surface? If not, what is at its surface?
3. What power or force enables black holes to draw things into them?
4. How close to a black hole do you have to be for its special effects to be apparent?
5. Can you use black holes to travel to different places in the universe?
6. Do black holes last forever? If not, what happens to them?

In this chapter you will discover…

- that Einstein's theory of general relativity predicts the existence of regions of space and time that are severely distorted by the extremely dense mass they contain
- that space and time are not separate entities
- how black holes arise
- the surprisingly simple theoretical properties of black holes
- that X rays and jets of gas are created near many black holes
- the fate of black holes
- the unsurpassed energy emitted by gamma-ray bursts

The Speed of Light Is Constant

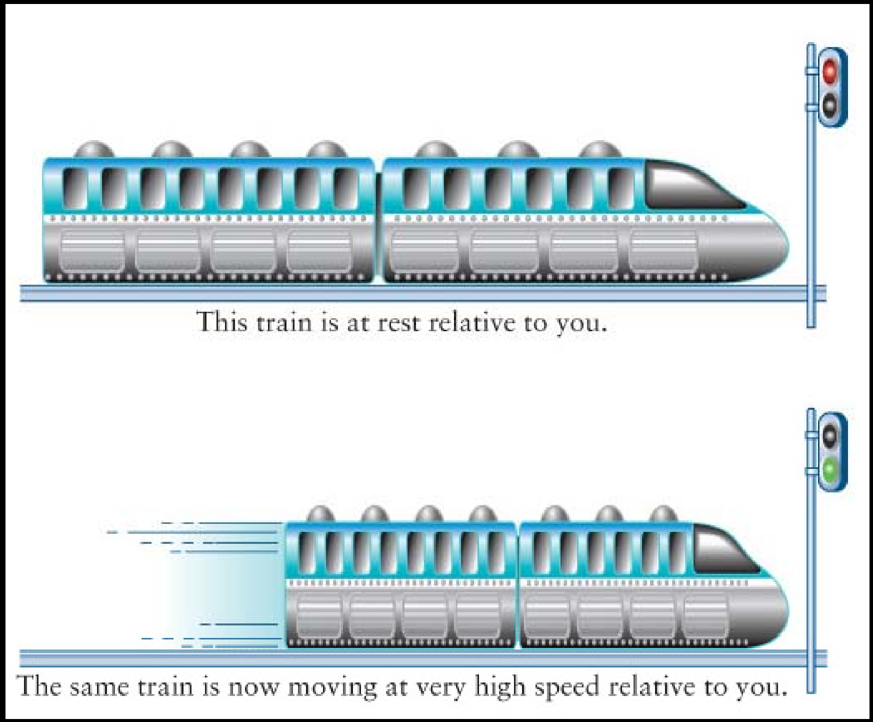




As seen from the ground, photons of light from the lamp are traveling toward the car with a speed $v = c$ (ignoring the slight decrease in speed due to the presence of the air).

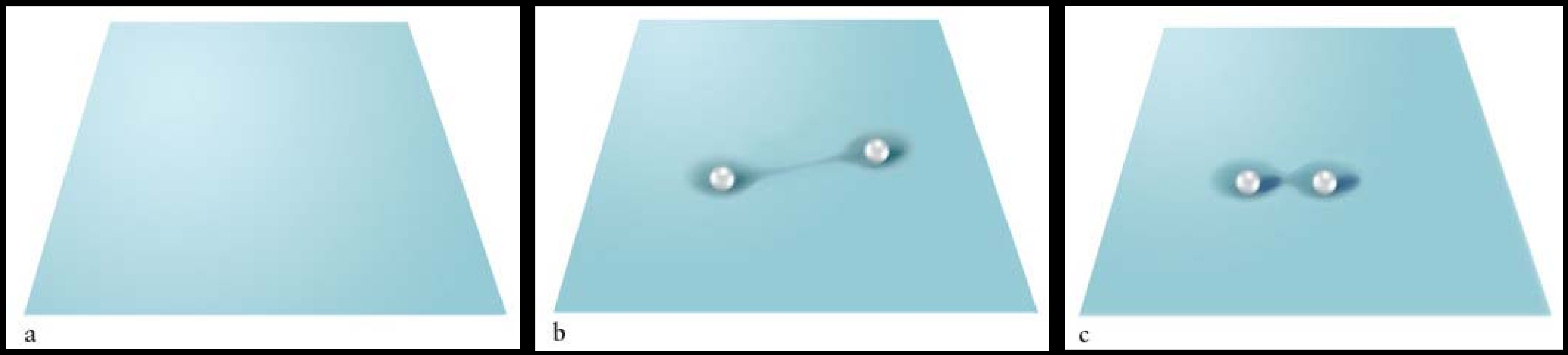
As seen from the car, moving toward the lamp at $v = 0.5c$, the photons are also traveling at the speed $v = c$. The difference in color between the light in the two figures is due to the Doppler shift.

Movement and Space



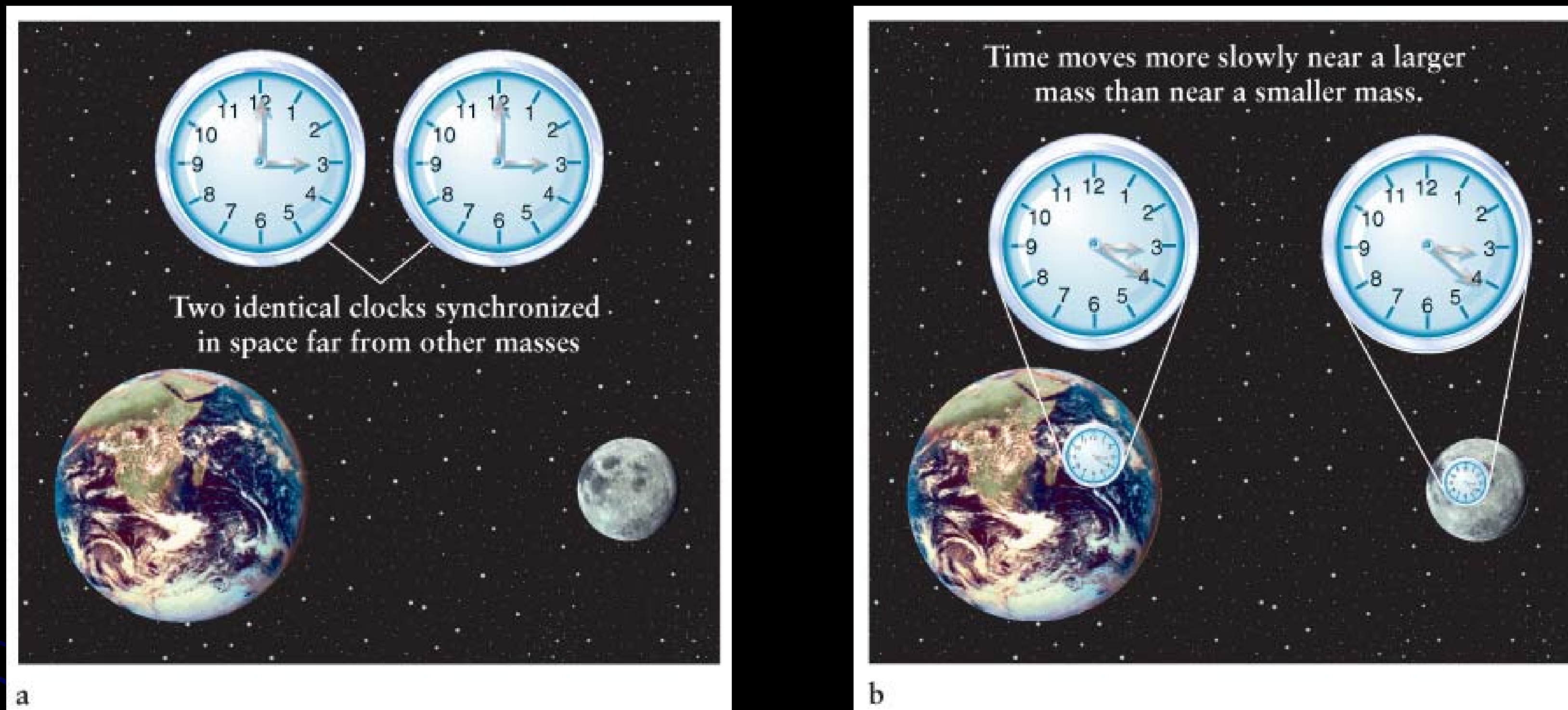
According to the theory of special relativity, the faster an object moves, the shorter it becomes in its direction of motion as observed by someone not moving with the object. It becomes infinitesimally short as its speed approaches the speed of light. The dimensions perpendicular to the object’s motion are unchanged.

Curved Spacetime



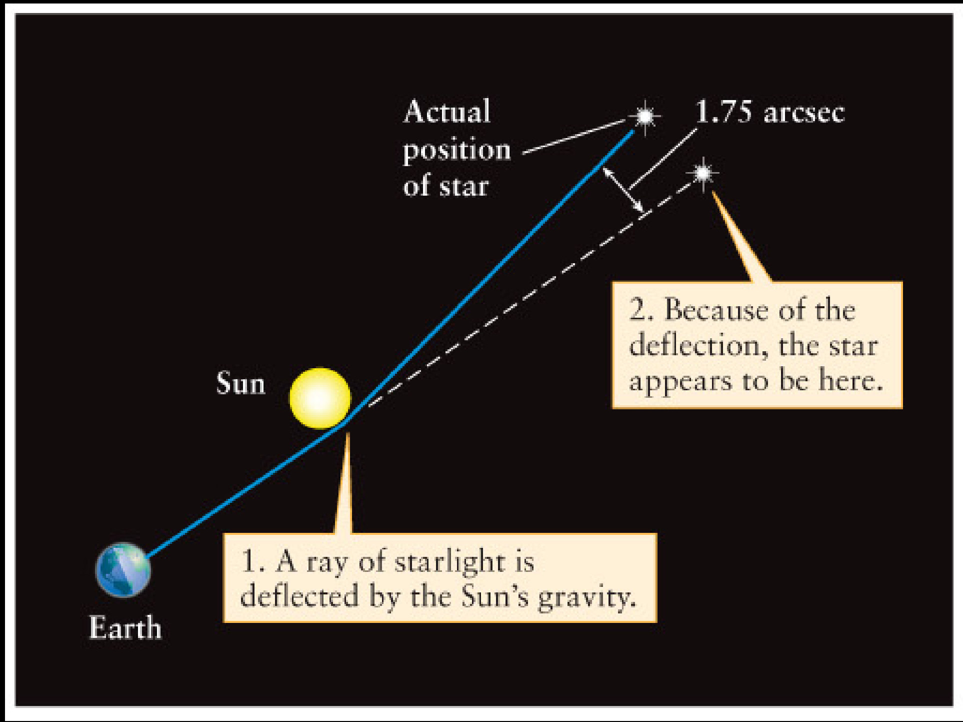
(a) This flat surface represents two dimensions in spacetime. In the absence of any matter in the spacetime, straight lines are straight in our intuitive sense (the sheet is flat). (b) In the presence of matter, spacetime curves, as shown by the curvature of the sheet when mass is laid on it. Straight lines, defined by the paths that light rays take, are no longer straight in the "usual" sense. Besides changing the path of photons, this curvature also creates gravity, which (c) pulls the two masses toward each other.

Time Slows Down Near Matter



(a) Two clocks in space set at exactly the same time are (b) brought to Earth and the Moon. From a vantage point far from Earth and the Moon, the clock on Earth is ticking more slowly than the clock on the Moon. This occurs because mass slows down the flow of time, and Earth has more mass (and a higher density, which adds to the effect) than the Moon.

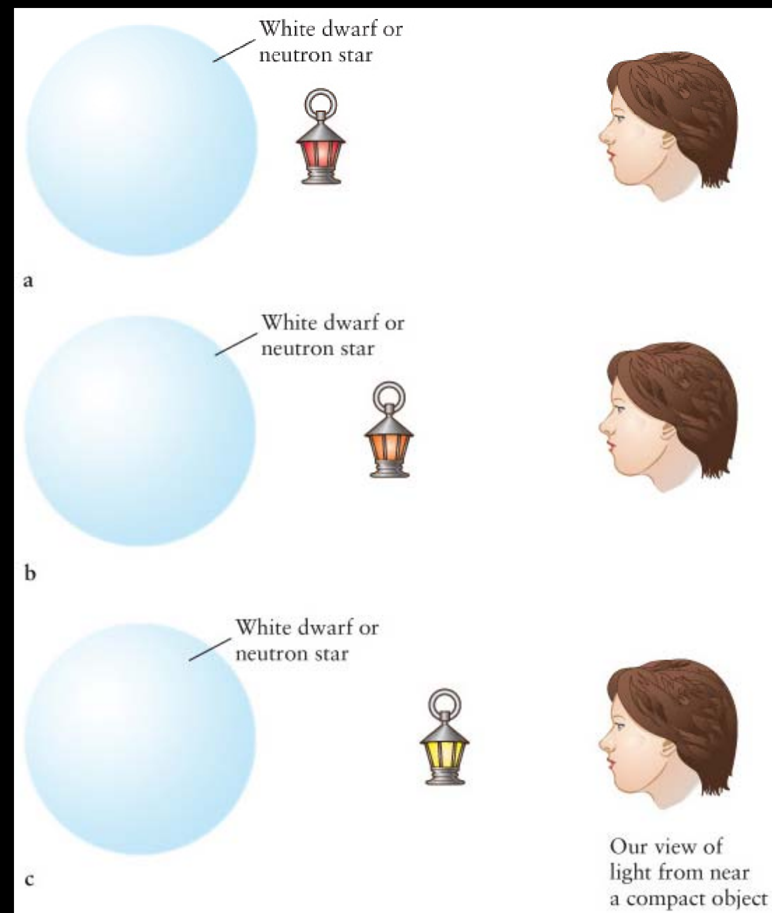
Curved Spacetime and the Path of Light



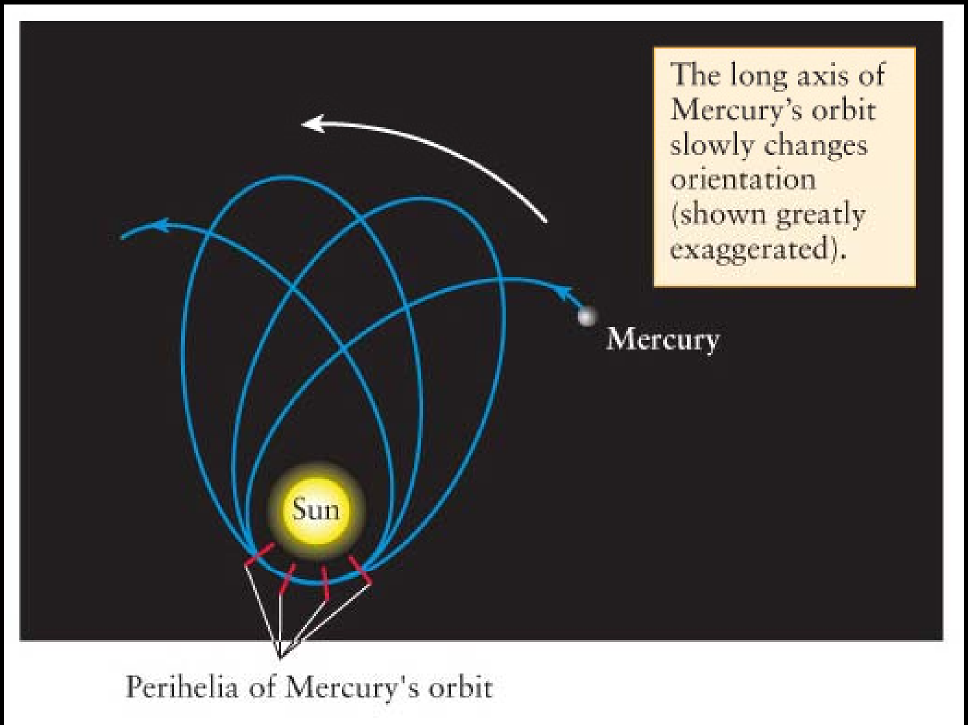
The warping of space by matter causes light to be deflected. This was the first prediction of general relativity to be confirmed, in 1919. This confirmation came when stars behind the Sun were observed during an eclipse. The star in this drawing was not observed where it was supposed to be, as a result of the Sun's gravity changing the path of its light.

Gravitational Redshift

The color of light from the same object located at different distances from a mass appears different as seen from far away. The photons that leave the vicinity of the massive object lose energy and therefore are redshifted. The closer the light source is to the mass, the redder the light appears; hence the name gravitational redshift. The same argument applies to light leaving the surfaces of different stars.

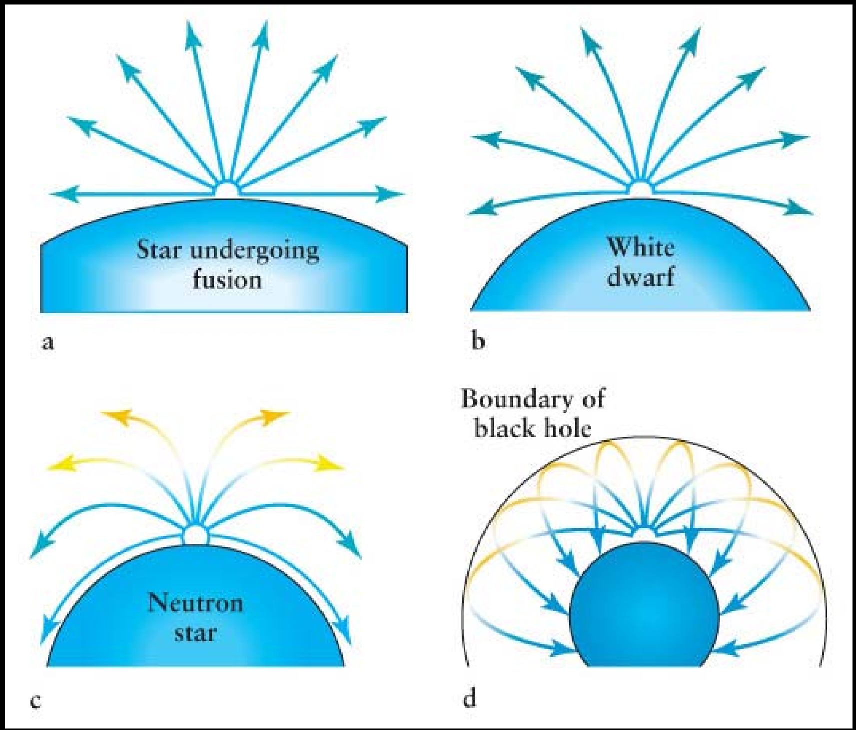


Mercury’s Orbit Explained by General Relativity



The location of Mercury’s perihelion (its position closest to the Sun) and its long axis of orbit change, or precess, with each orbit. This occurs because of the gravitational influences of the other planets plus the curvature of space as predicted by Einstein’s theory of general relativity. The amount of precession is inconsistent with the prediction of the orbit made by Newton’s law of gravity alone.

Trapping of Light by a Black Hole

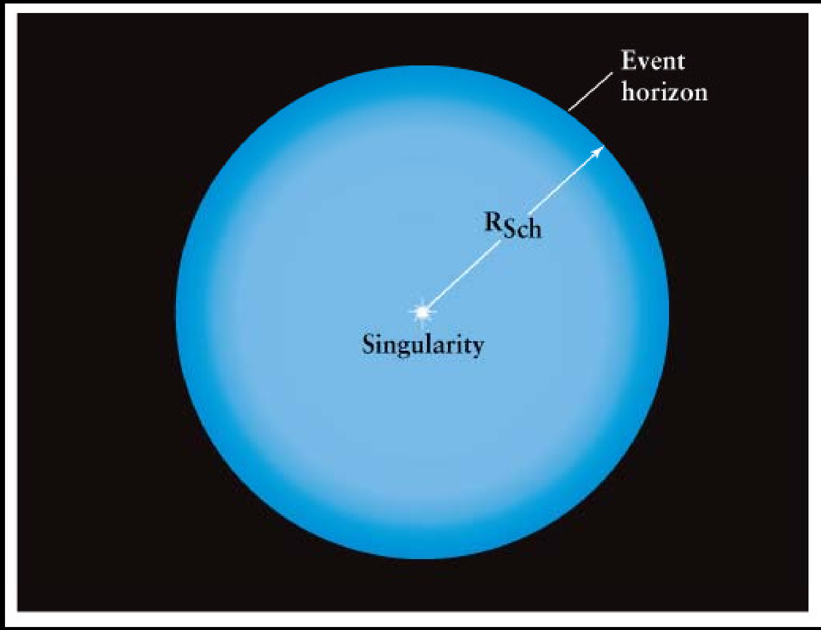


(a) The paths and colors of light rays departing from a main-sequence, giant, or supergiant star are affected very little by the star's gravitational force. (b) Light leaving the vicinity of a white dwarf curves and redshifts more, whereas (c) near a neutron star, some of the photons actually return to the star's surface. (d) Inside a black hole, all light remains trapped. Most photons curve back in, except those that fly straight upward, which become infinitely redshifted, thereby disappearing.

Laser Interferometer Gravitational Wave Observatory (LIGO)

Located in Hanford, Washington, this is one of several gravitational wave (colloquially, gravity wave) detectors around the world. It has two perpendicular arms, each 4 km long. Gravity waves that pass the detector cause unequal changes in the lengths of the arms. These changes are detected by lasers inside each arm.

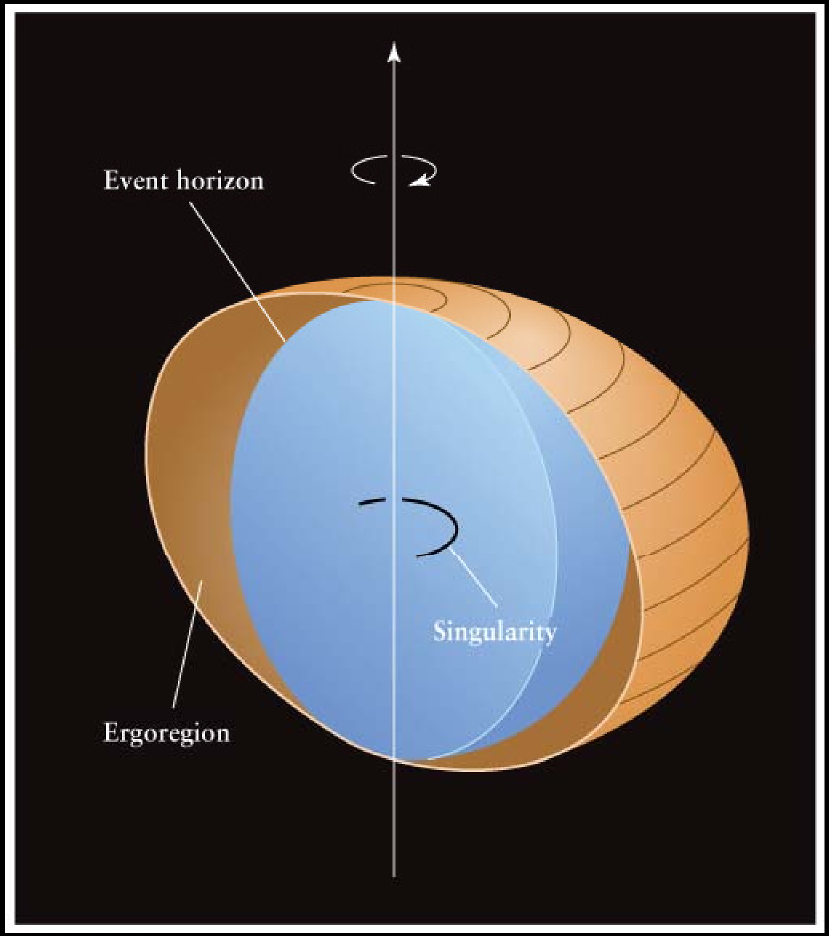
Structure of a Schwarzschild (Nonrotating) Black Hole



- A nonrotating black hole has only two notable features: its singularity and its boundary. Its mass, called a singularity because it is so dense, collects at its center. The spherical boundary between the black hole and the outside universe is called the event horizon. The distance from the center to the event horizon is the Schwarzschild radius, R_{Sch}. There is no solid, liquid, or gas surface at the event horizon. In fact, except for its location at the boundary of the black hole, an event horizon lacks any features at all.

Structure of a Kerr (Rotating) Black Hole

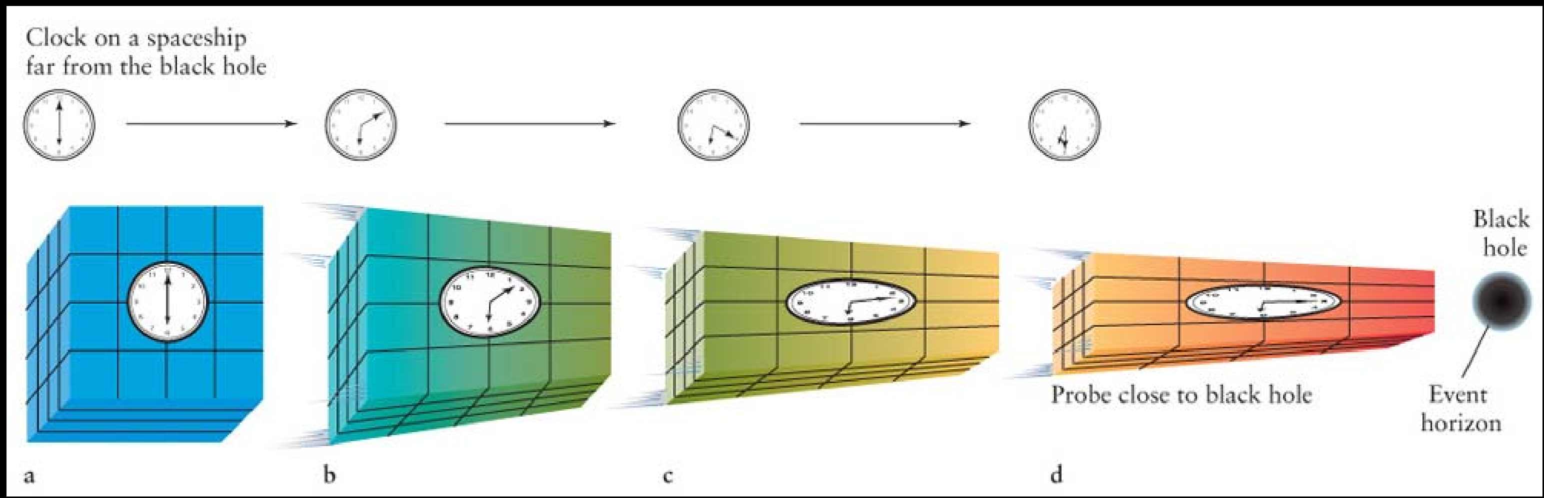
Rotating black holes are only slightly more complex than nonrotating ones. The singularity of a Kerr black hole is located in an infinitely thin ring around the center of the hole. It appears as an arc in this cutaway drawing. The event horizon is again a spherical surface. There is also a doughnut-shaped region, called the ergoregion, just outside the event horizon, in which nothing can remain at rest. Space in the ergoregion is being curved or pulled around by the rotating black hole.



Swirling Space in an Ergoregion

Just as the chocolate in this blender is being dragged by the spinning blade, so too is space dragged by a spinning (Kerr) black hole.

Effect of a Black Hole's Tidal Force on Infalling Matter



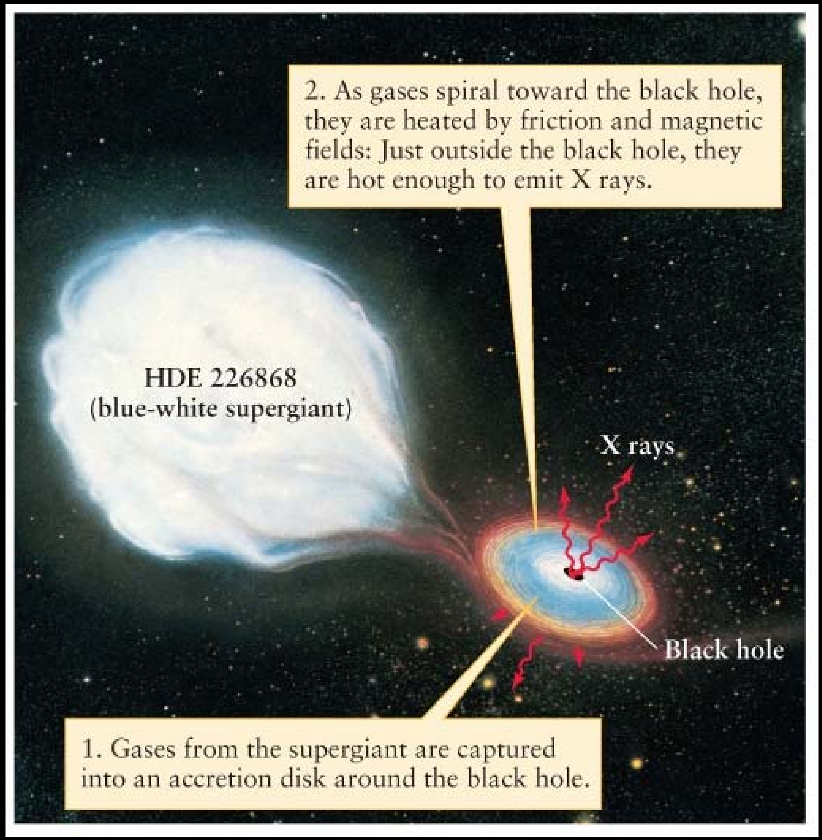
(a) A cube-shaped probe 1500 km from a 5-solar-mass black hole. (b, c, d) Near the Schwarzschild radius, the probe is pulled long and thin by the difference in the gravitational forces felt by its different sides. This tidal effect is a greatly magnified version of the Moon's gravitational force on Earth. The probe changes color as its photons undergo extreme gravitational redshift and time slows down on the probe, as seen from far away.

Formation of an Accretion Disk

Just as the water in this photograph swirls around waiting to get down the drain, the matter pulled toward a black hole spirals inward. Angular momentum of the infalling gas and dust causes them to form an accretion disk around the hole.

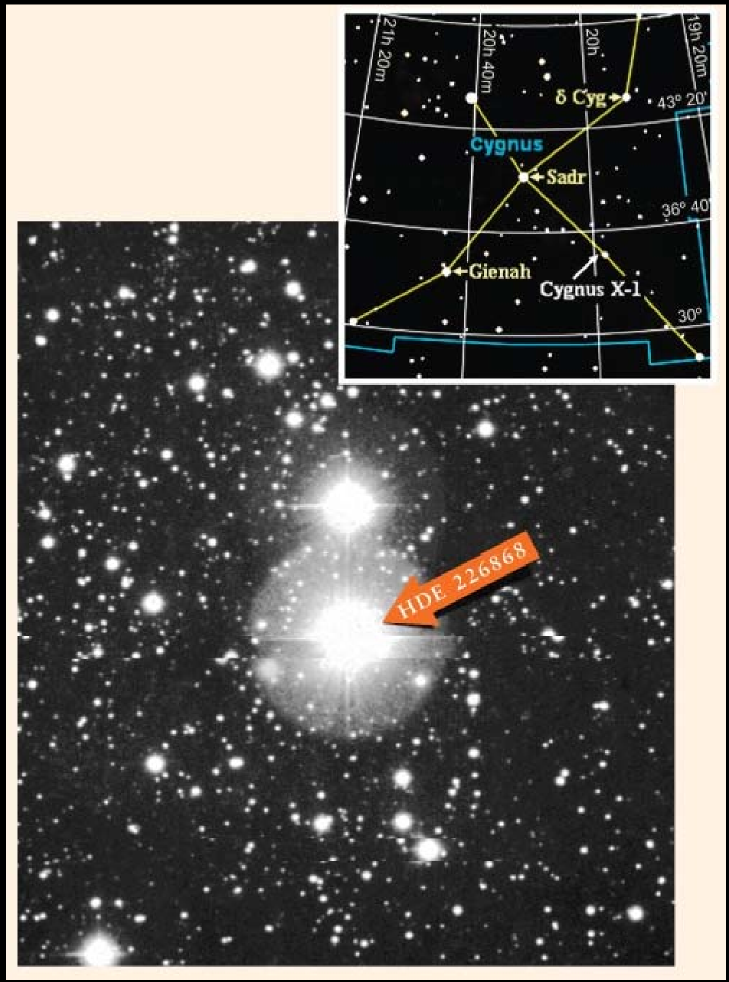
X Rays Generated by Accretion of Matter Near a Black Hole

Stellar-remnant black holes, such as Cygnus X-1, LMC X-3, V404 Cygni, and probably A0620-00, are detected in close binary star systems. This drawing of the Cygnus X-1 system shows how gas from the 30-solar-mass companion star, HDE 226868, transfers to the black hole, which has at least 11 solar masses. This process creates an accretion disk. As the gas spirals inward, friction and compression heat it so much that the gas emits X rays, which astronomers can detect.

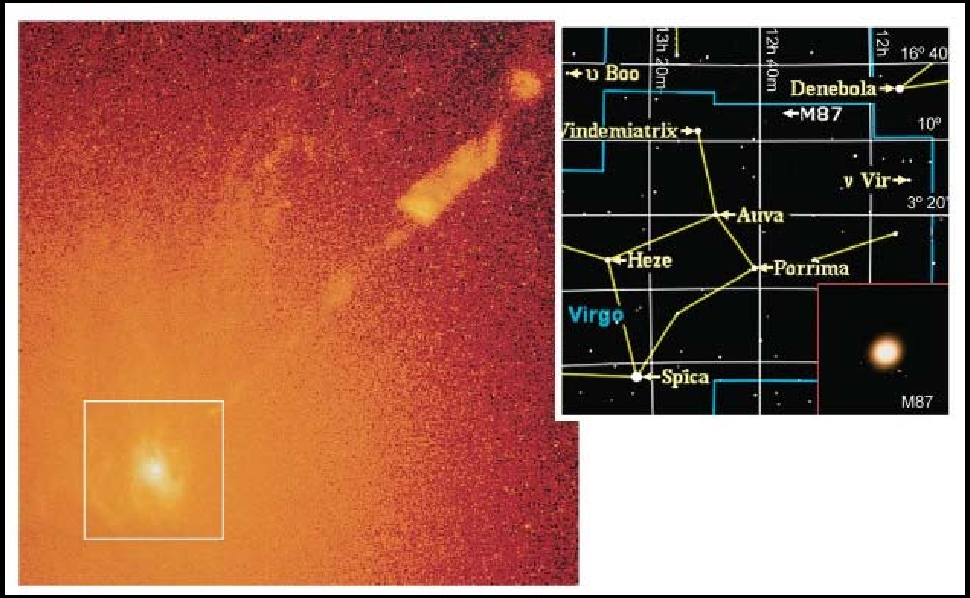


HDE 226868

This star is the visual companion of the X-ray source Cygnus X-1. This binary system is located about 8000 ly from Earth and contains a black hole of at least 11 solar masses in orbit with HDE 226868, a B0 blue supergiant star. The photograph was taken with the 200-in. telescope at Palomar Observatory on Palomar Mountain, north of San Diego. The slightly dimmer star above is an optical double that is not part of the binary system.



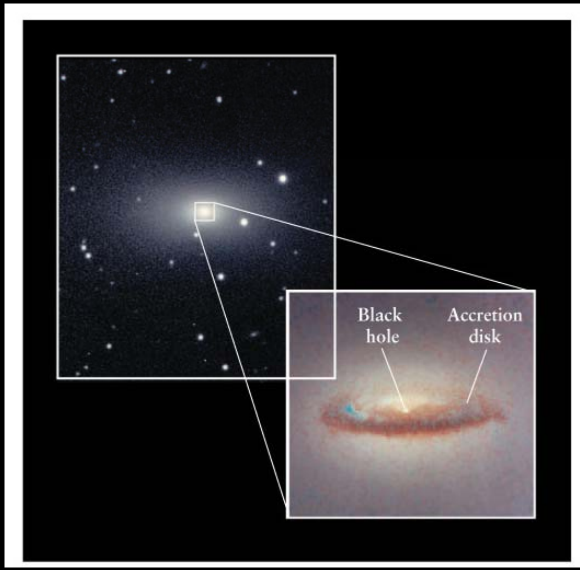
Supermassive Black Hole



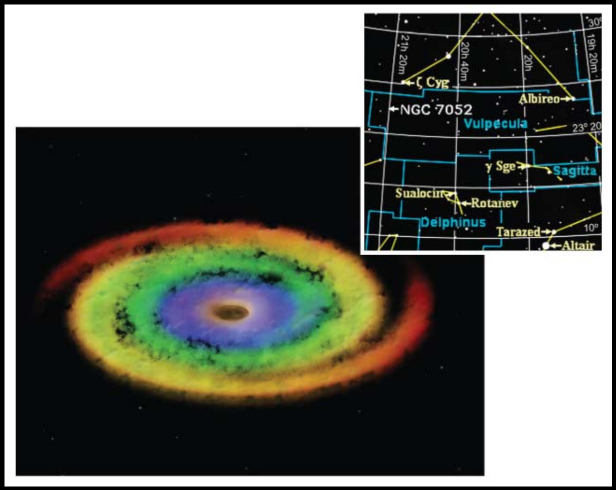
The bright region in the center of galaxy M87 has stars and gas held in tight orbits by a black hole. M87's bright nucleus (center of the region in the white box) is only about the size of the solar system but it pulls on the nearby stars with so much force that astronomers calculate that it is a 3-billion-solar-mass black hole. One of the bright jets of gas shooting out perpendicular to the black hole's accretion disk is visible at the upper right on this image.

Accretion Disk Around a Supermassive Black Hole

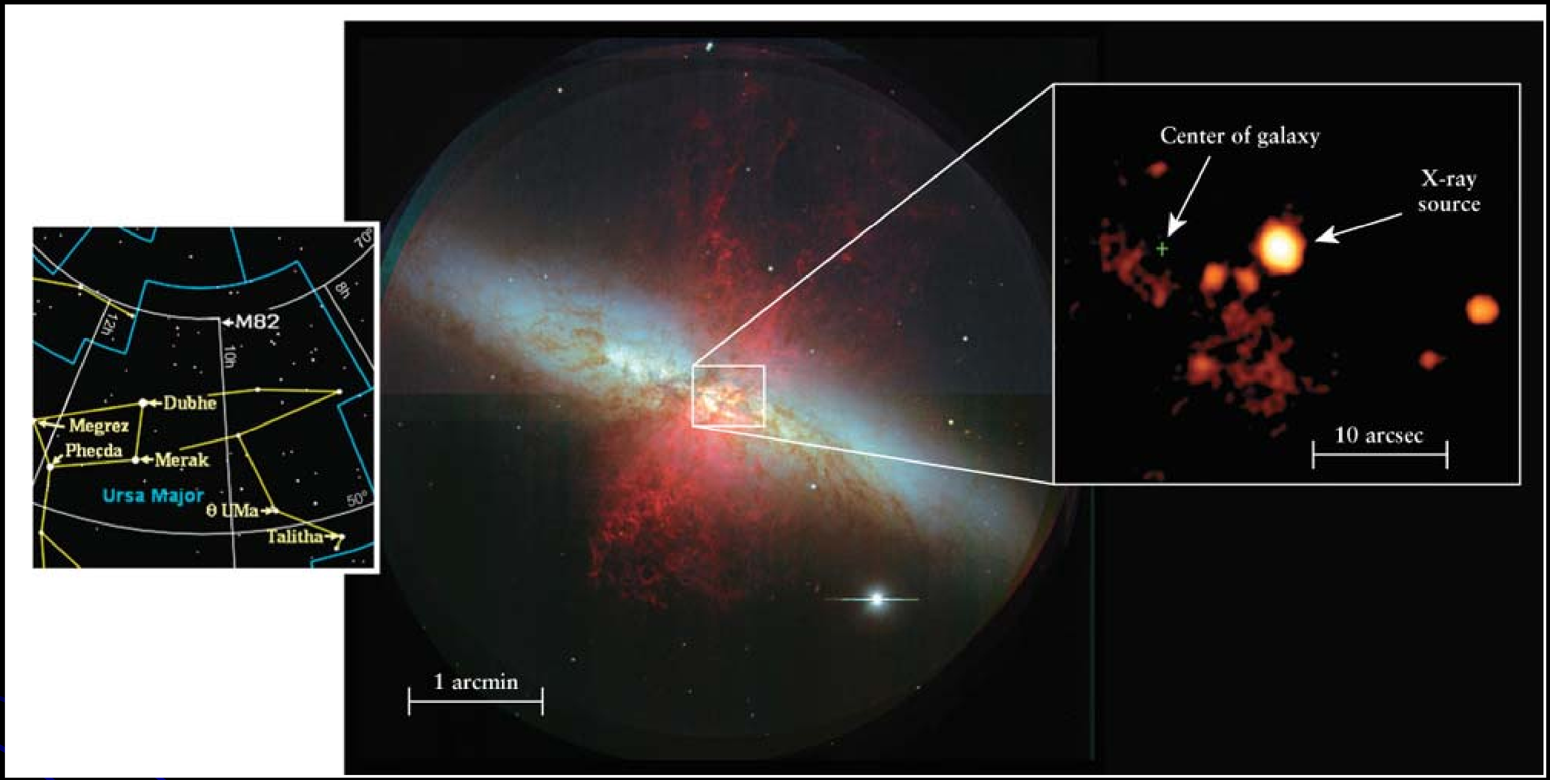
Swirling around a 300-million-solar-mass black hole in the center of the galaxy NGC 7052, this disk of gas and dust is 3700 ly across. The gas is cascading into the black hole, which will consume it all over the next few billion years. The black hole appears bright because of light emitted by the hot, accreting gas outside its event horizon. NGC 7052 is 191 million ly from Earth in the constellation Vulpecula.



This drawing shows how the gases spiraling inward in an accretion disk heat up as they approach the black hole. Color coding follows Wien's displacement law: red (coolest), followed by orange, yellow, green, blue, and violet (hottest).

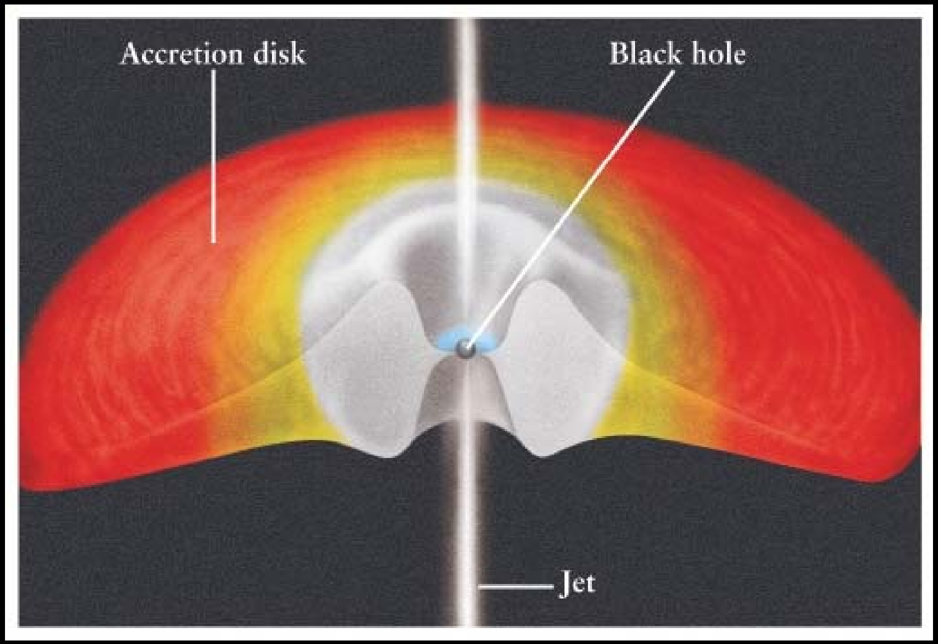


An "Intermediate-Mass" Black Hole



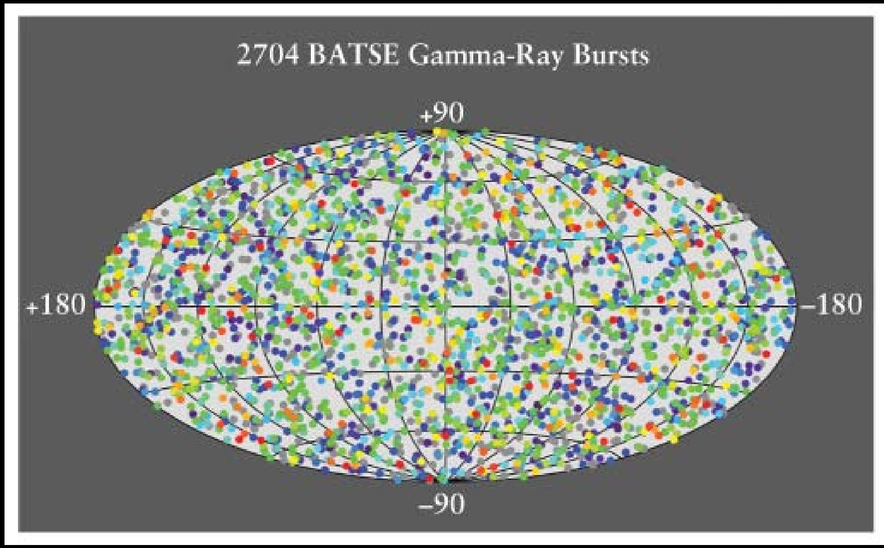
M82 is an unusual galaxy in the constellation Ursa Major. The inset shows an image of the central region of M82 from the *Chandra* X-ray Observatory. The bright, compact X-ray source shown varies in its light output over a period of months. The properties of this source suggest that it is a black hole of roughly 500 solar masses.

Jets Created by a Black Hole in a Binary System



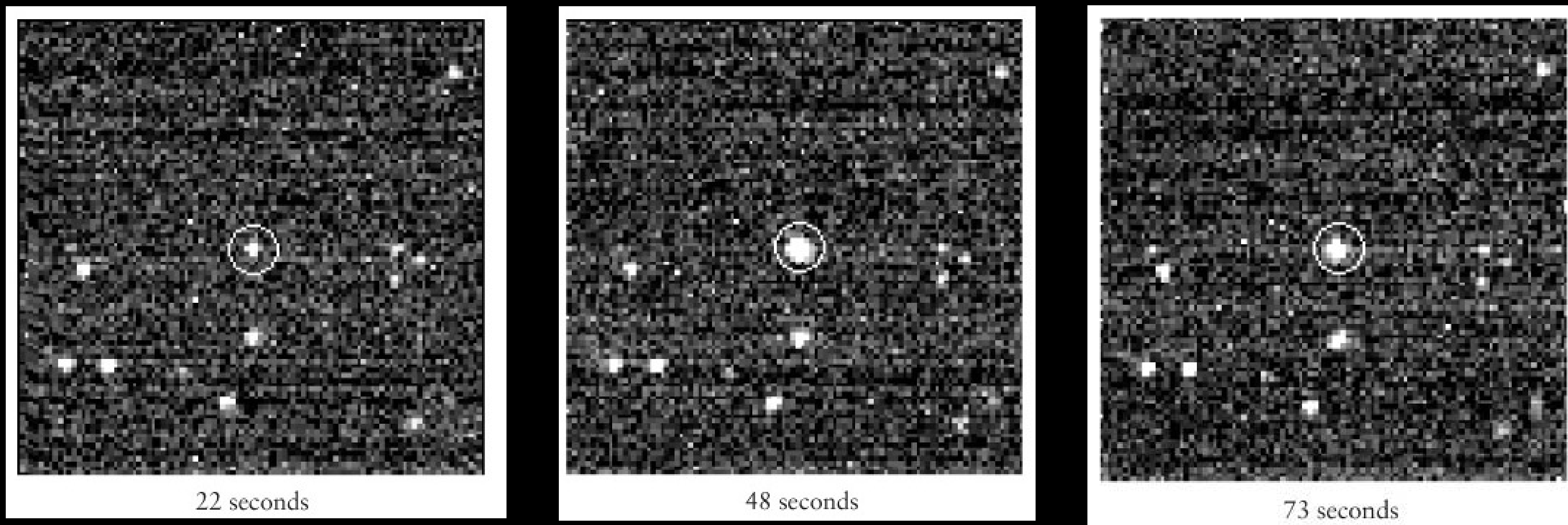
Some of the matter spiraling inward in the accretion disk around a black hole is superheated and redirected outward to produce two powerful jets of particles that travel at close to the speed of light. The companion star is off to one side of this drawing.

The Most Powerful Known Gamma Ray Bursts



Gamma-ray bursts have been observed everywhere in the sky, indicating that, unlike X-ray bursters, most do not originate in the disk of the Milky Way Galaxy. This map of the entire sky “unfolded” onto the page shows 2704 bursts detected by the Burst and Transient Source Experiment (BATSE) aboard the Compton Gamma-Ray Observatory. The colors indicate the brightness of the bursts; they are coded brightest in red, dimmest in violet. Gray dots indicate incomplete information about the burst strength.

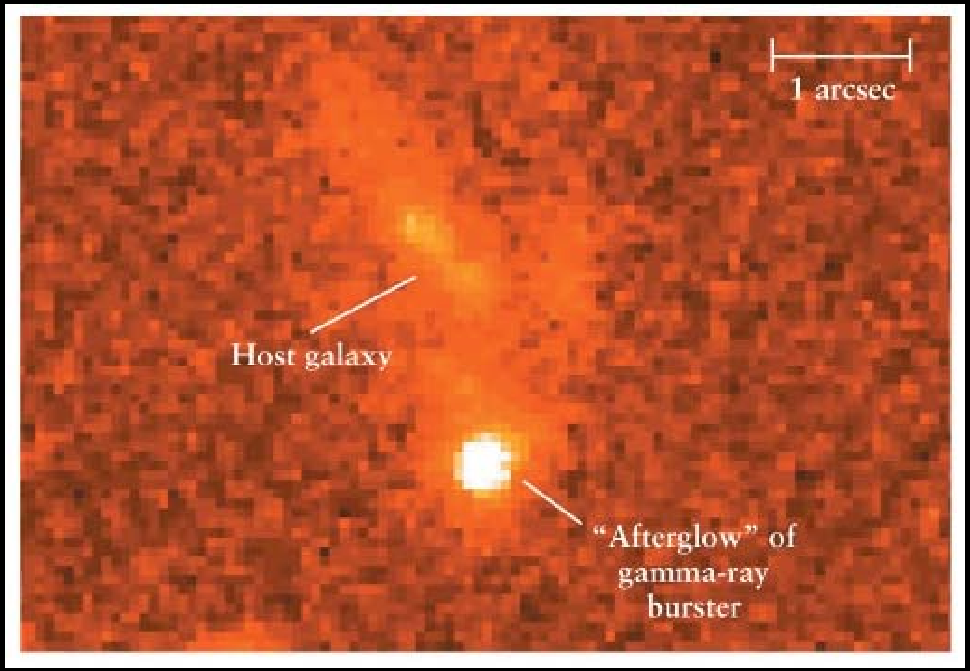
Gamma-Ray Bursts



22 seconds 48 seconds 73 seconds

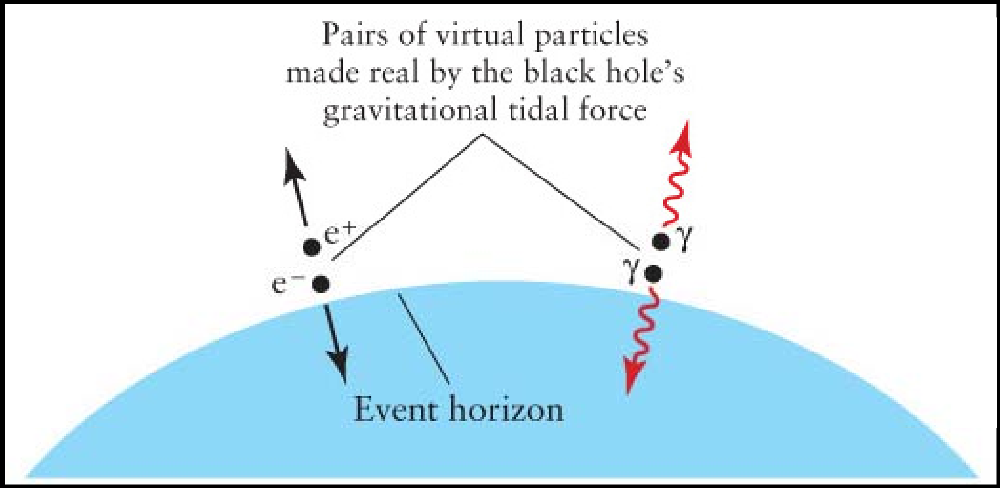
In 1999, astronomers photographed the visible-light counterpart of a 100-s gamma-ray burst some 9 billion ly away in the constellation Boötes. The times indicated are after the burst began.

The Host Galaxy of a Gamma-Ray Burst



The Hubble Space Telescope recorded this visible-light image in 1999, 16 days after a gamma-ray burst was observed at this location. The image (color-coded to show contrast rather than true color) reveals a faint galaxy that is presumed to be the home of the gamma-ray burst. The galaxy has a bright blue color, indicating the presence of many recently formed stars.

Evaporation of a Black Hole



Throughout the universe, pairs of virtual particles spontaneously appear and disappear so quickly that they do not violate any laws of nature. The tidal force just outside of the event horizon of a black hole is strong enough to tear apart two virtual particles that appear there before they destroy each other. The gravitational energy that goes into separating them makes them real and, therefore, permanent. At least one of each pair of newly created particles falls into the black hole. Sometimes the other particle escapes into the universe. Because the gravitational energy used to create the particles came from the black hole, the hole loses mass and shrinks, eventually evaporating completely. Here we see just a few particles in the making: an electron (e^-), a positron (e^+), and a pair of photons (γ).

Mount Everest

Primordial black holes, formed at the beginning of time, may have had masses similar to those of Mount Everest, as shown here. Calculations indicate that the universe is old enough for such black holes to have evaporated. Their final particle production rate is so high that they should look as though they are exploding.

Summary of Key Ideas

Black Hole Basics

- If a stellar corpse is more massive than about 3 solar masses, gravitational compression overcomes neutron degeneracy and forces it to collapse further and become a black hole.
- A black hole is an object so dense that the escape velocity from it exceeds the speed of light.

The Relativity Theories

- Special relativity reveals that space and time are intimately connected and change with an observer's relative motion.
- As seen by observers moving more slowly, the faster an object moves, the slower time passes for it (time dilation) and the shorter it becomes (length contraction).
- According to general relativity, mass causes space to curve and time to slow down. These effects are significant only near large masses or compact objects.

Inside a Black Hole

- The event horizon of a black hole is a spherical boundary where the escape velocity equals the speed of light. No matter or electromagnetic radiation can escape from inside the event horizon. The distance from the center of the black hole to the event horizon is called the Schwarzschild radius.
- The matter inside a black hole collapses to a singularity. The singularity for nonrotating matter is a point at the center of the black hole. For rotating matter, the singularity is a ring inside the event horizon.
- Matter inside a black hole has only three physical properties: mass, angular momentum, and electric charge.

Inside a Black Hole

- Nonrotating black holes are called Schwarzschild black holes. Rotating black holes are called Kerr black holes. The event horizon of a Kerr black hole is surrounded by an ergoregion in which all matter must constantly move to avoid being pulled into the black hole.
- Matter that approaches a black hole's event horizon is stretched and torn by the extreme tidal forces generated by the black hole; light from the matter is redshifted; and time slows down.
- Black holes can evaporate by the Hawking process, in which virtual particles near the black hole become real. These transformations of virtual particles into real ones decrease the mass of a black hole until eventually, it disappears.

Evidence of Black Holes

- Observations indicate that some binary star systems harbor black holes. In such systems, gases captured by the black hole from the companion star heat up and emit detectable X rays and jets of gas.
- Supermassive black holes exist in the centers of many galaxies. Intermediate-mass black holes exist in clusters of stars. Very low mass (primordial) black holes may have formed at the beginning of the universe.

Gamma-Ray Bursts

- Gamma-ray bursts are events believed to be caused by some supernovae and by the collisions of dense objects, such as neutron stars or black holes. Some occur in the Milky Way and nearby galaxies, whereas many occur billions of light-years away from Earth.
- Typical gamma-ray bursts occur for a few tens of seconds and emit more energy than the Sun will radiate over its entire 10-billion-year lifetime.

Key Terms

accretion disk
black hole
cosmic censorship
ergoregion
event horizon
gamma-ray burst
gravitational radiation
gravitational redshift
gravitational wave
Hawking process
intermediate-mass black hole
Kerr black hole
primordial black hole
Schwarzschild black hole
Schwarzschild radius
singularity
spacetime
supermassive black hole
theory of general relativity
theory of special relativity
virtual particle
wormhole
Wolf-Rayet stars

WHAT DID YOU THINK?

- *Are black holes empty holes in space? If not, what are they?*
- No, black holes contain highly compressed matter—they are not empty.

WHAT DID YOU THINK?

- *Does a black hole have a solid surface? If not, what is at its surface?*
- No. The surface of a black hole, called the event horizon, is empty space. No stationary matter exists there.

WHAT DID YOU THINK?

- *What power or force enables black holes to draw things into them?*
- The only force that pulls things in is the gravitational attraction of the matter and energy in the black hole.

WHAT DID YOU THINK?

- *How close to a black hole do you have to be for its special effects to be apparent?*
- About 100 times the Schwarzschild radius.

WHAT DID YOU THINK?

- *Can you use black holes to travel to different places in the universe?*
- No. Most astronomers believe that the wormholes predicted by general relativity do not exist.

WHAT DID YOU THINK?

- *Do black holes last forever? If not, what happens to them?*
- No, black holes evaporate.