



Lecture Outlines

## Chapter 22

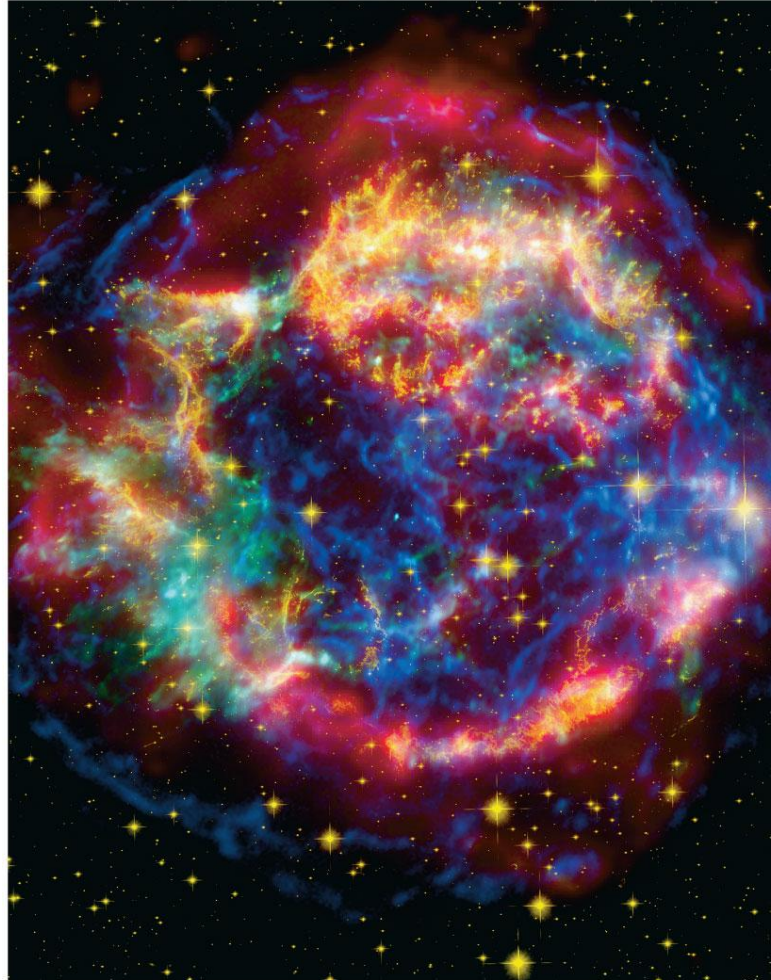
***Astronomy Today***

***7th Edition***

Chaisson/McMillan

# Chapter 22

## Neutron Stars and Black Holes



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# Units of Chapter 22

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Tests of General Relativity

Gravity Waves: A New Window on the  
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# 22.1 Neutron Stars

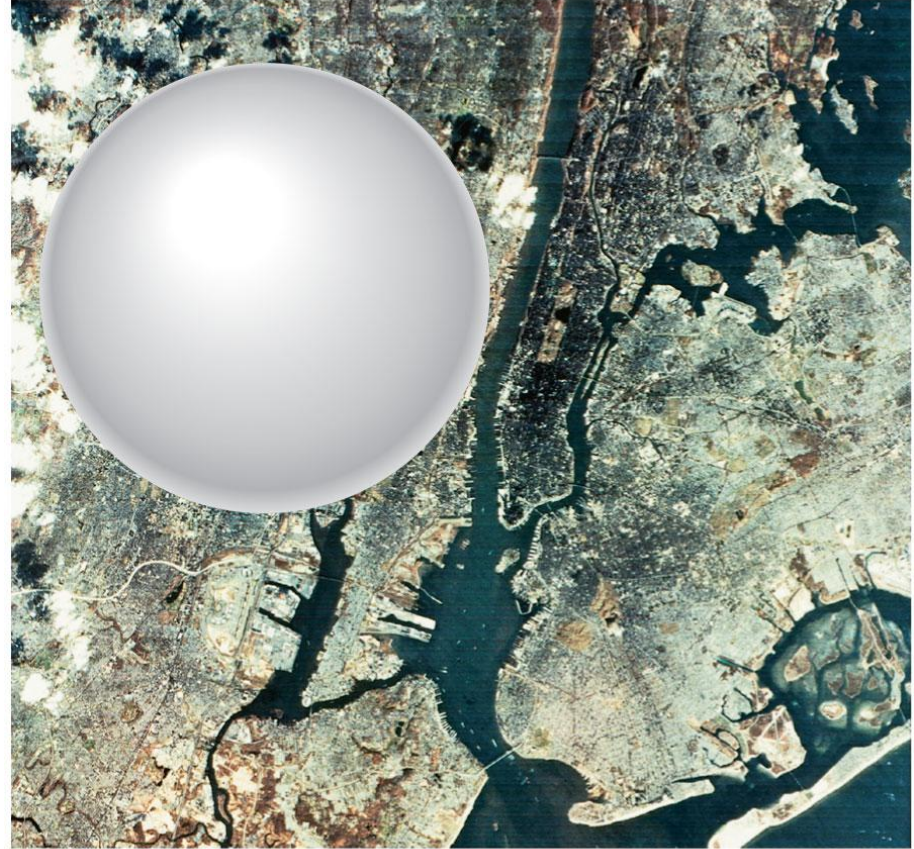
After a Type I supernova, little or nothing remains of the original star.

After a Type II supernova, part of the core may survive. It is very dense—as dense as an atomic nucleus—and is called a neutron star.



# 22.1 Neutron Stars

Neutron stars, although they have 1–3 solar masses, are so dense that they are very small. This image shows a 1-solar-mass neutron star, about 10 km in diameter, compared to Manhattan:



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# 22.1 Neutron Stars

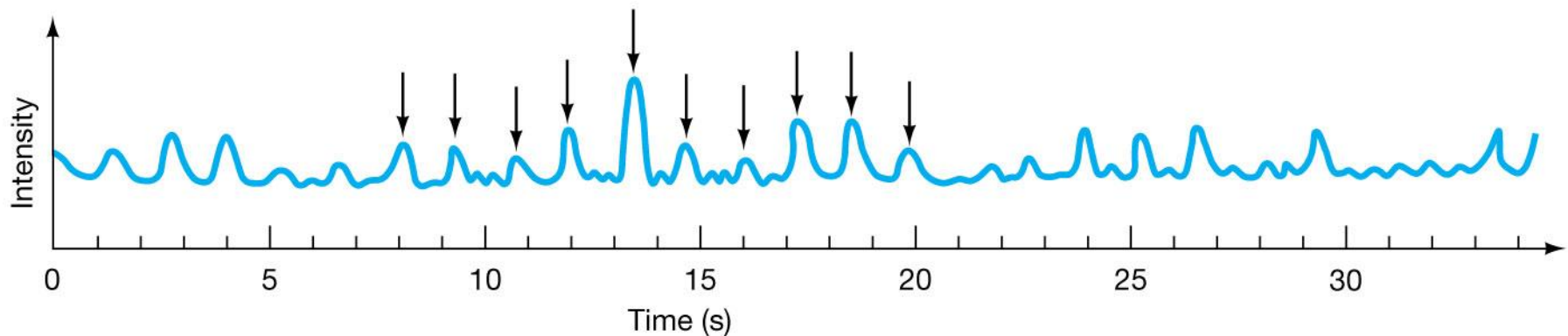
Other important properties of neutron stars (beyond mass and size):

- **Rotation**—as the parent star collapses, the neutron core spins very rapidly, conserving angular momentum. Typical periods are fractions of a second.
- **Magnetic field**—again as a result of the collapse, the neutron star's magnetic field becomes enormously strong.

# 22.2 Pulsars

The first pulsar was discovered in 1967. It emitted extraordinarily regular pulses; nothing like it had ever been seen before.

After some initial confusion, it was realized that this was a neutron star, spinning very rapidly.



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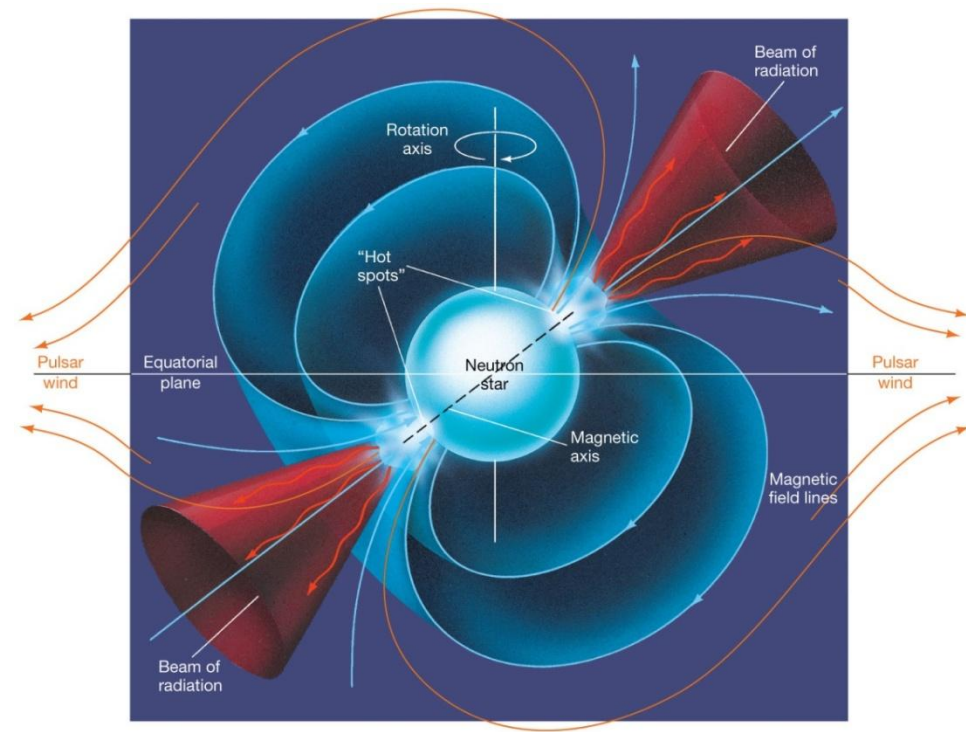


# 22.2 Pulsars

But why would a neutron star flash on and off?

This figure illustrates the lighthouse effect responsible:

Strong jets of matter are emitted at the magnetic poles. If the rotation axis is not the same as the magnetic axis, the two beams will sweep out circular paths. If the Earth lies in one of those paths, we will see the star pulse.



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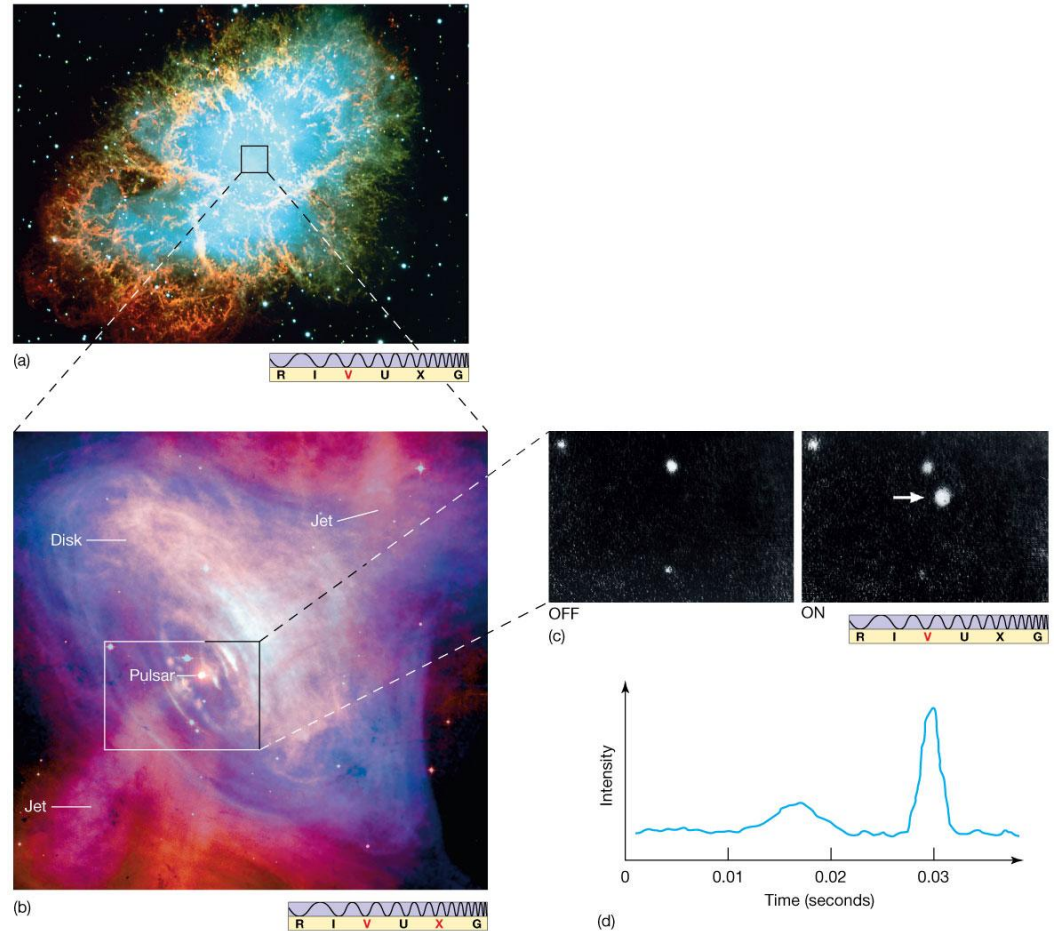
# 22.2 Pulsars

Pulsars radiate their energy away quite rapidly; the radiation weakens and stops in a few tens of millions of years, making the neutron star virtually undetectable.

Pulsars also will not be visible on Earth if their jets are not pointing our way.

# 22.2 Pulsars

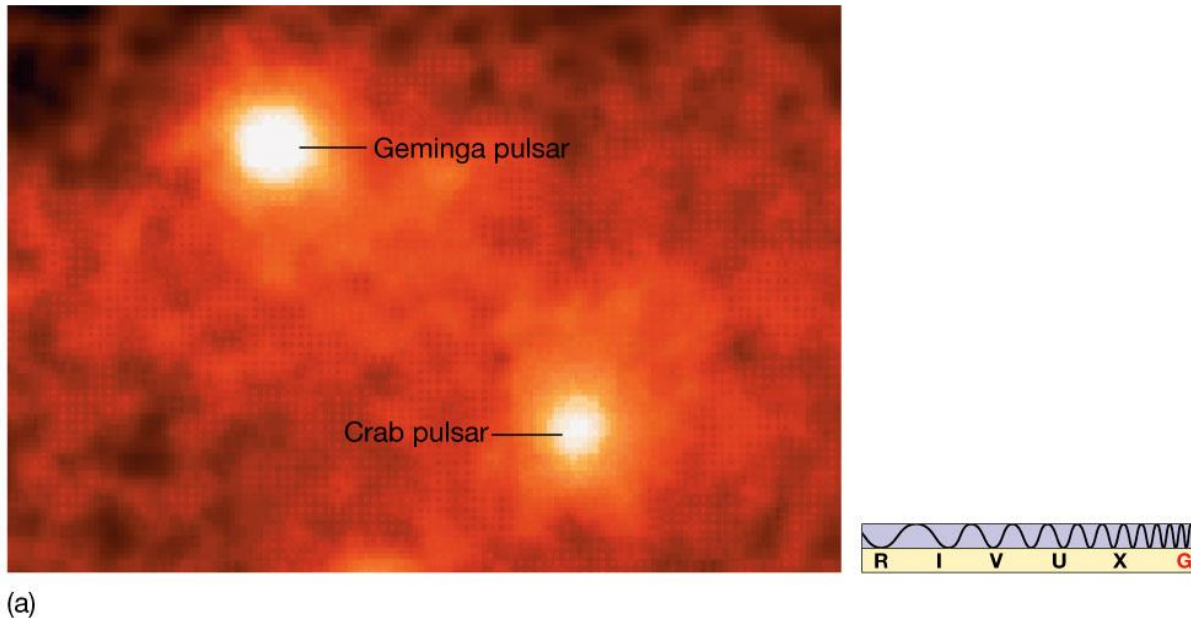
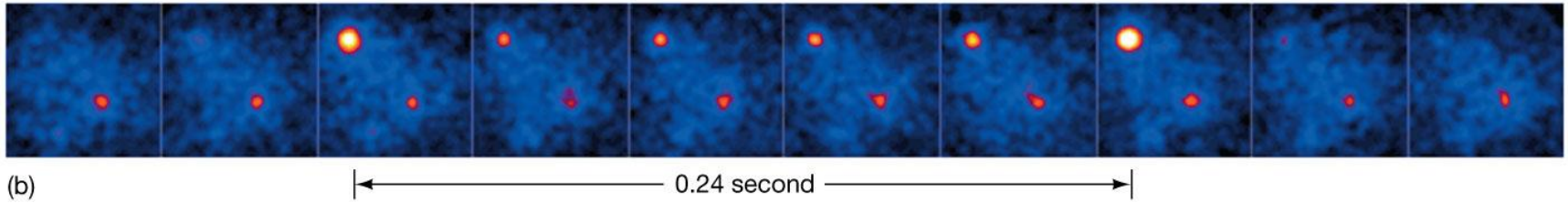
There is a pulsar at the center of the Crab Nebula; the images show it in the “off” and “on” states. The disk and jets are also visible:



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# 22.2 Pulsars

The Crab pulsar also pulses in the gamma-ray spectrum:



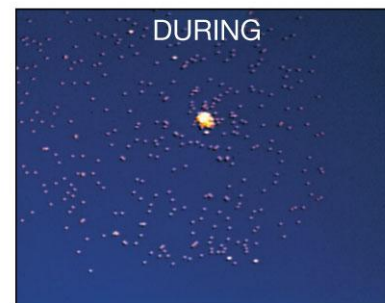
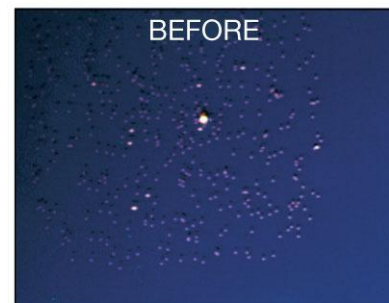
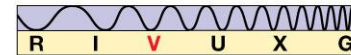
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# 22.3 Neutron-Star Binaries

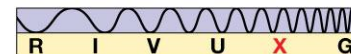
Bursts of X-rays have been observed near the center of our galaxy. A typical one appears below, as imaged in the X-ray spectrum:



(a)



(b)



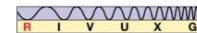
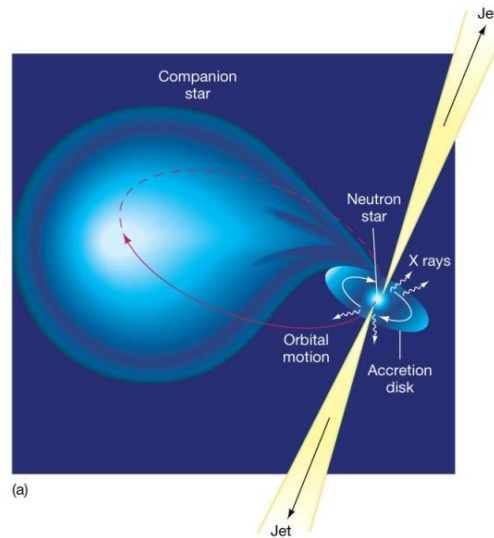
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# 22.3 Neutron-Star Binaries

These X-ray bursts are thought to originate on neutron stars that have binary partners.

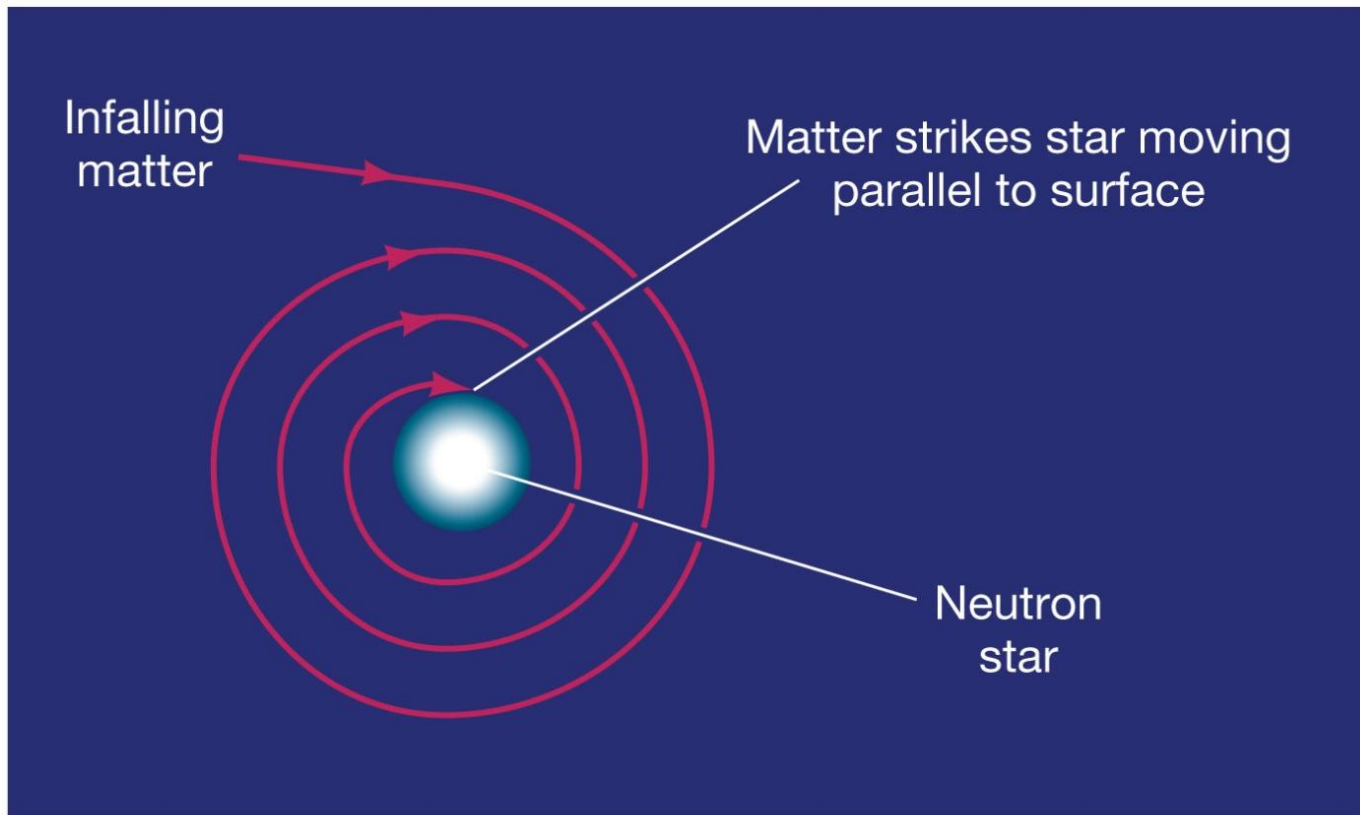
The process is similar to a nova, but much more energy is emitted due to the extremely strong gravitational field of the neutron star.





# 22.3 Neutron-Star Binaries

Most pulsars have periods between 0.03 and 0.3 seconds, but a new class of pulsar was discovered in the early 1980s: the millisecond pulsar.

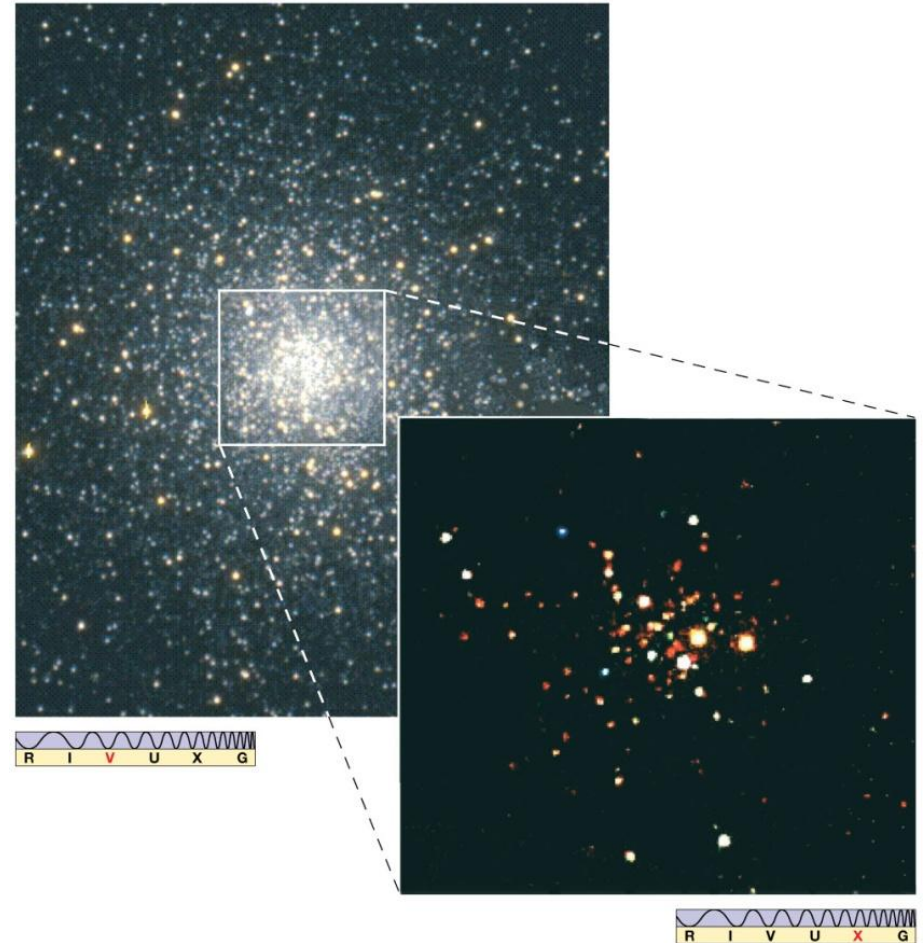


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# 22.3 Neutron-Star Binaries

Millisecond pulsars are thought to be “spun-up” by matter falling in from a companion.

This globular cluster has been found to have 108 separate X-ray sources, about half of which are thought to be millisecond pulsars:

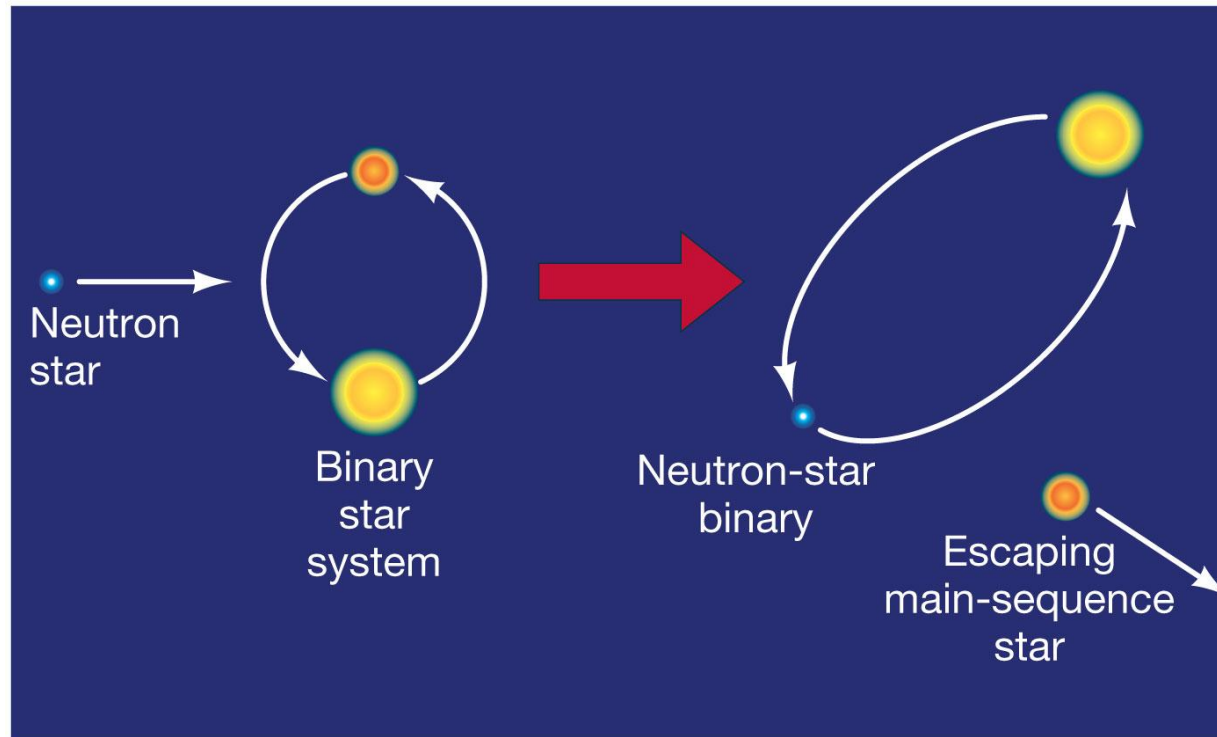


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# 22.3 Neutron-Star Binaries

In 1992, a pulsar was discovered whose period had unexpected, but very regular, variations.

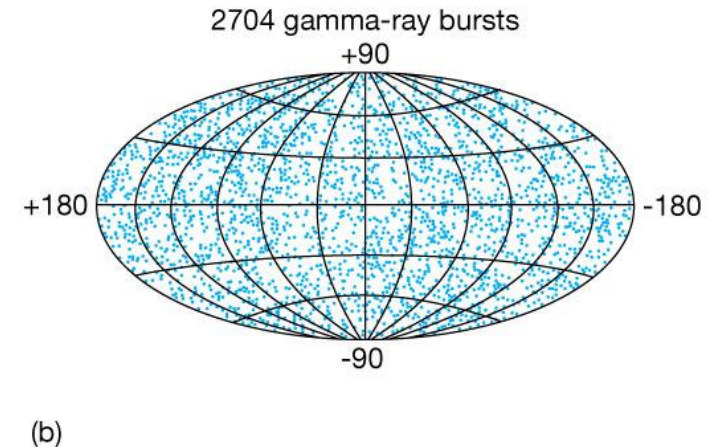
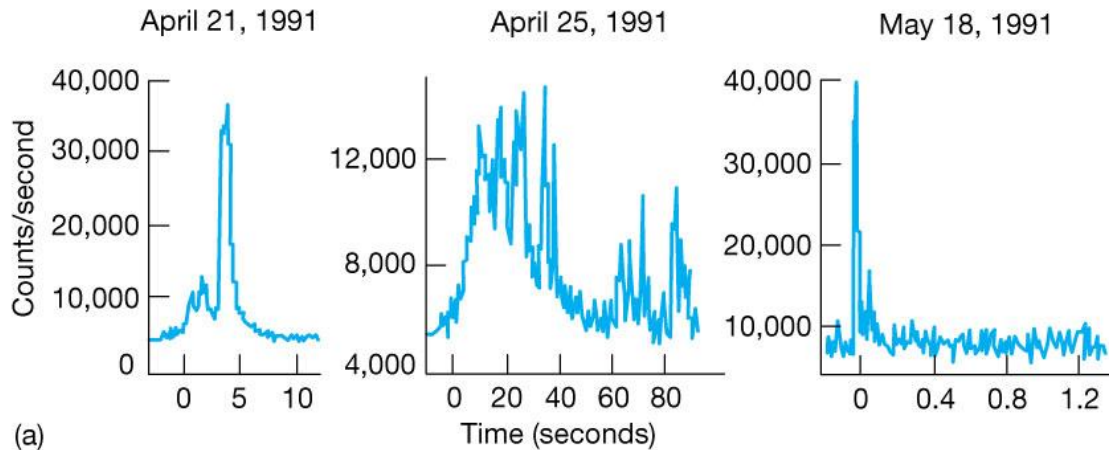
These variations were thought to be consistent with a planet, which must have been picked up by the neutron star, not the progenitor star:



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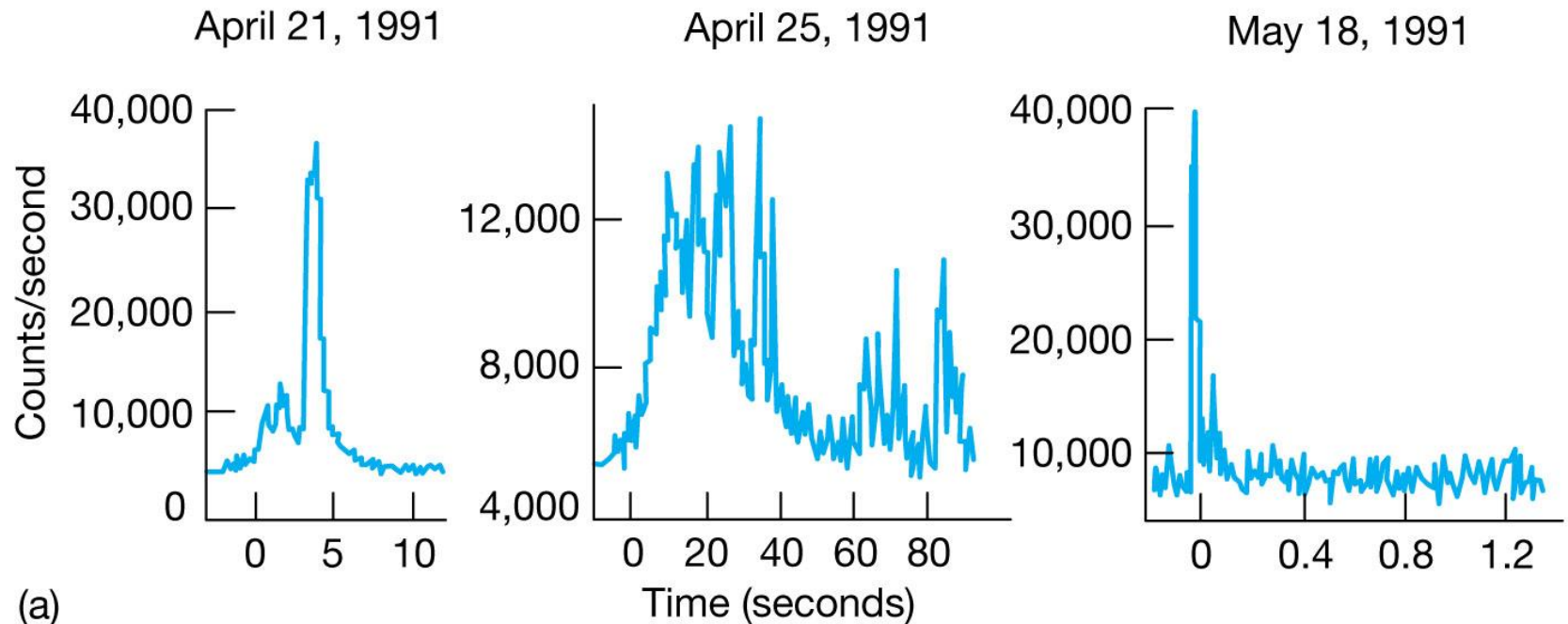
# 22.4 Gamma-Ray Bursts

Gamma-ray bursts also occur, and were first spotted by satellites looking for violations of nuclear test-ban treaties. This map of where the bursts have been observed shows no “clumping” of bursts anywhere, particularly not within the Milky Way. Therefore, the bursts must originate from outside our Galaxy.



# 22.4 Gamma-Ray Bursts

These are some sample luminosity curves for gamma-ray bursts:



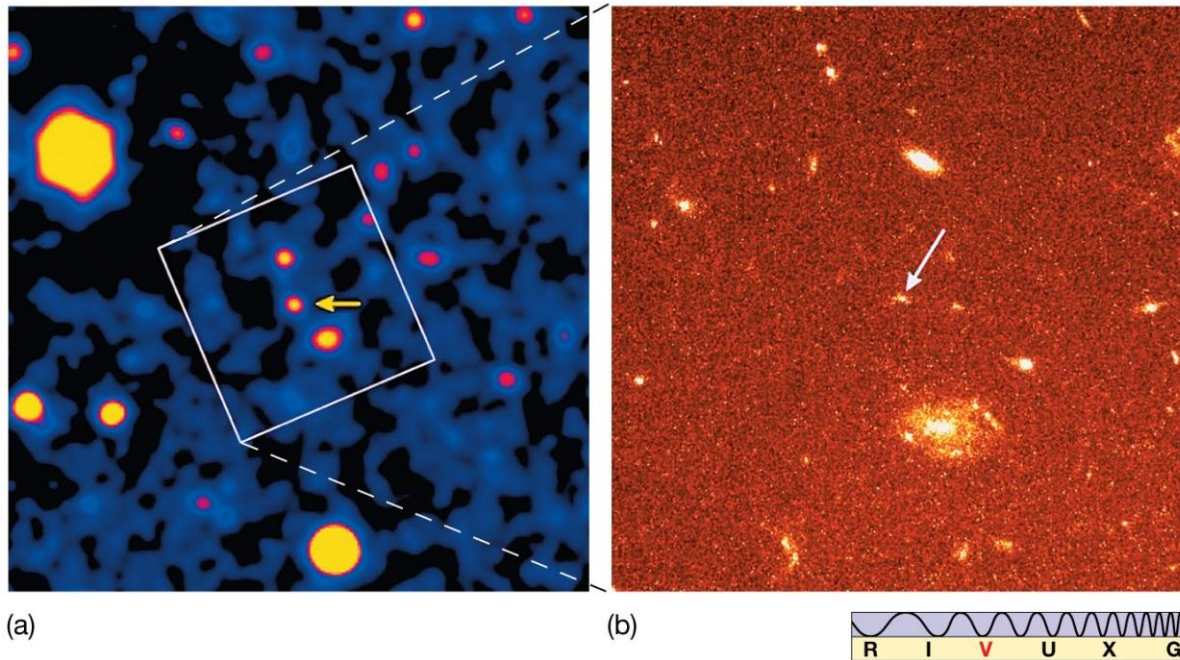
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# 22.4 Gamma-Ray Bursts

Distance measurements of some gamma bursts show them to be very far away—2 billion parsecs for the first one measured.

Occasionally the spectrum of a burst can be measured, allowing distance determination:

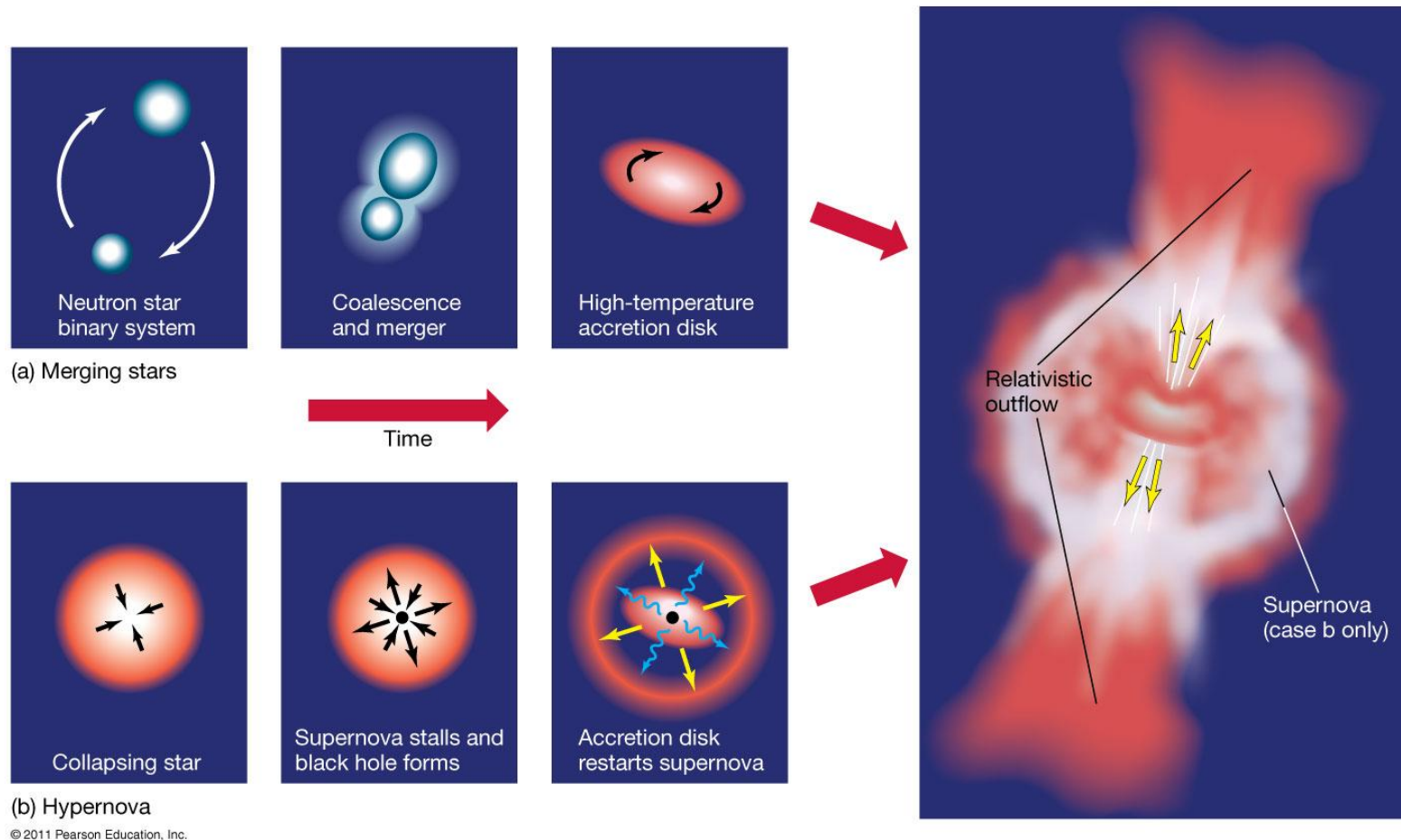


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# 22.4 Gamma-Ray Bursts

Two models—merging neutron stars or a hypernova—have been proposed as the source of gamma-ray bursts:



# 22.5 Black Holes

The mass of a neutron star cannot exceed about 3 solar masses. If a core remnant is more massive than that, nothing will stop its collapse, and it will become smaller and smaller and denser and denser.

Eventually, the gravitational force is so intense that even light cannot escape. The remnant has become a black hole.

# 22.5 Black Holes

The radius at which the escape speed from the black hole equals the speed of light is called the Schwarzschild radius.

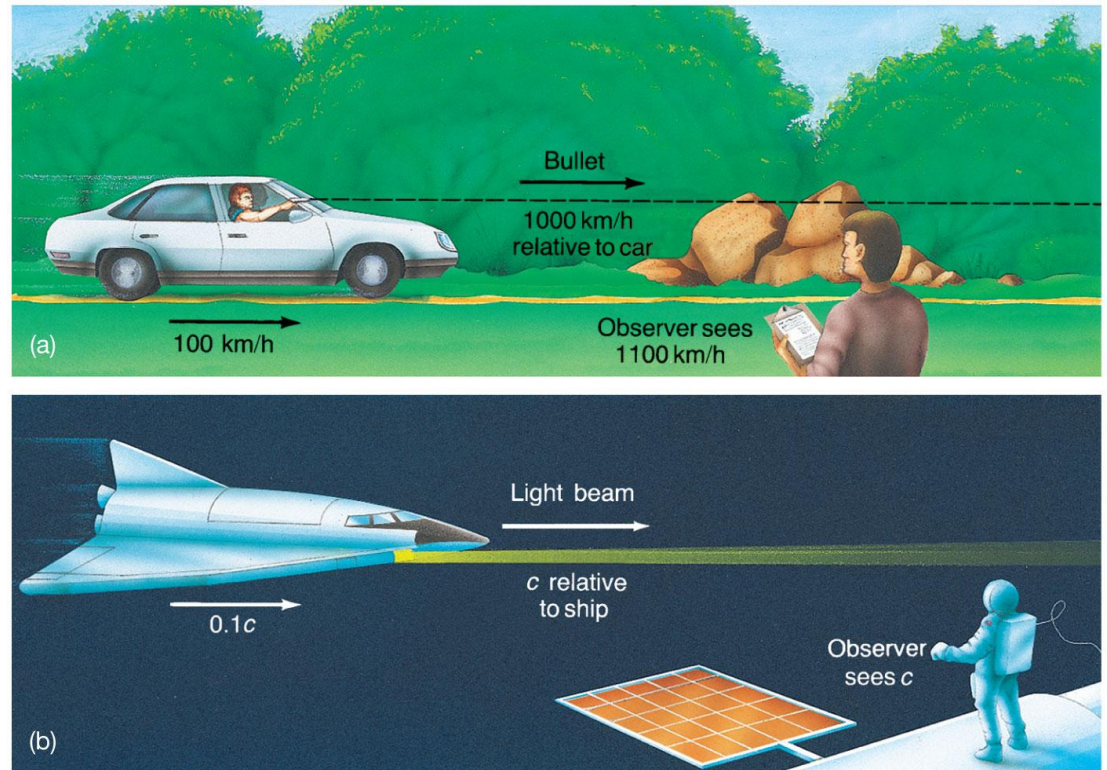
The Earth's Schwarzschild radius is about a centimeter; the Sun's is about 3 km.

Once the black hole has collapsed, the Schwarzschild radius takes on another meaning—it is the event horizon. Nothing within the event horizon can escape the black hole.

# 22.6 Einstein's Theories of Relativity

Special relativity:

1. The speed of light is the maximum possible speed, and it is always measured to have the same value by all observers:



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# 22.6 Einstein's Theories of Relativity

Special relativity (cont.):

2. There is no absolute frame of reference, and no absolute state of rest.

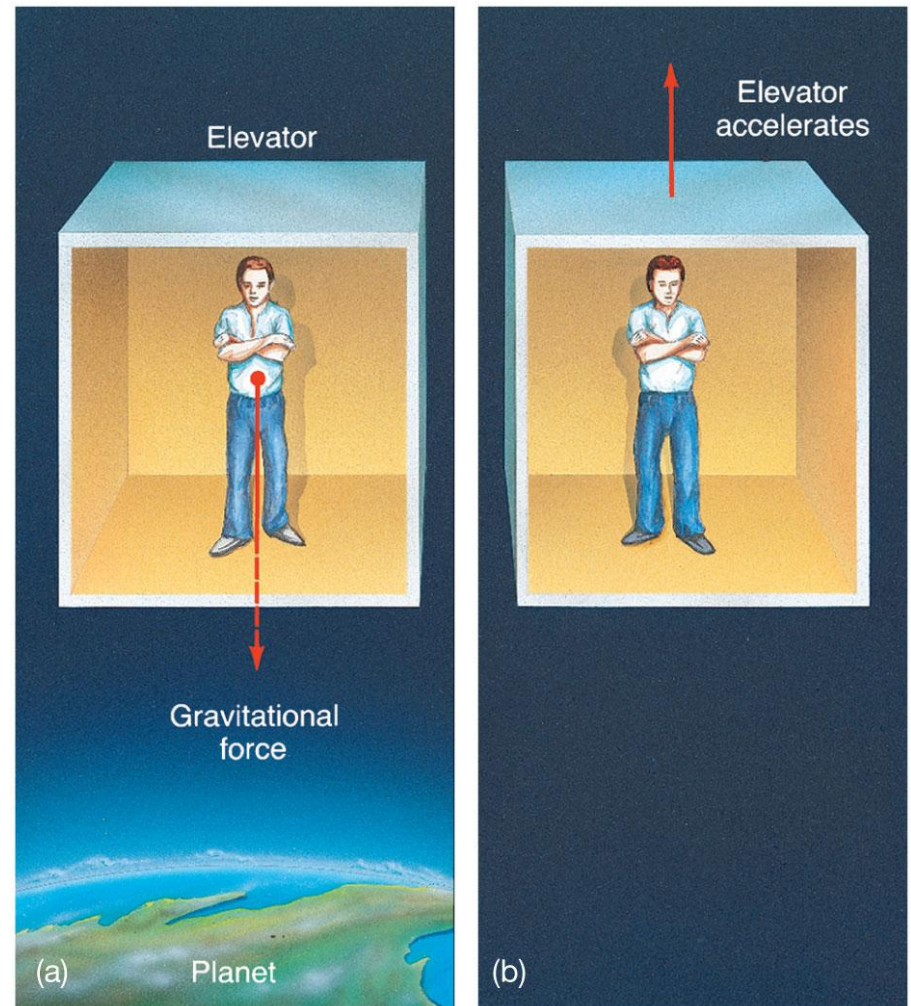
3. Space and time are not independent but are unified as spacetime.



# 22.6 Einstein's Theories of Relativity

General relativity:

It is impossible to tell from within a closed system whether one is in a gravitational field or accelerating.



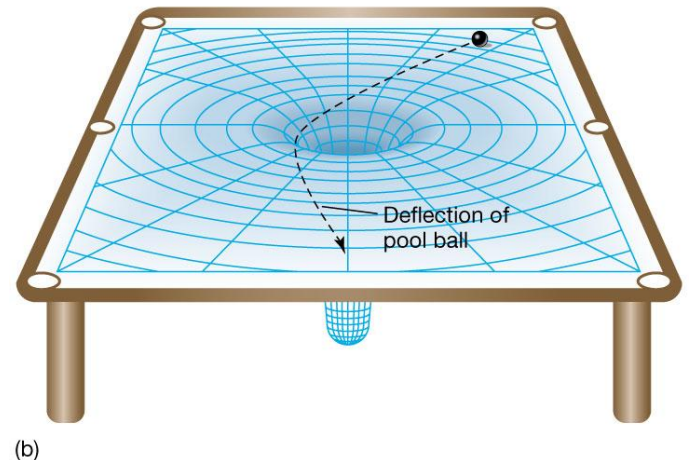
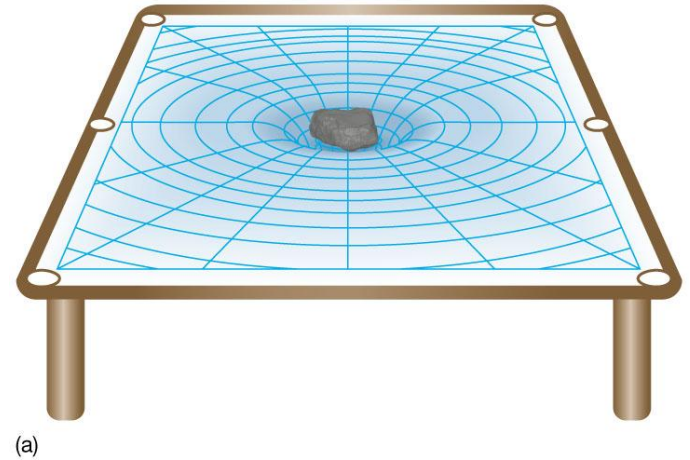
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# 22.6 Einstein's Theories of Relativity

Matter tends to warp spacetime, and in doing so redefines straight lines (the path a light beam would take):

A black hole occurs when the “indentation” caused by the mass of the hole becomes infinitely deep.



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# More Precisely 22-1: Special Relativity

In the late 19th century, Michelson and Morley did an experiment to measure the variation in the speed of light with respect to the direction of the Earth's motion around the Sun.

They found no variation—light always traveled at the same speed. This later became the foundation of special relativity.

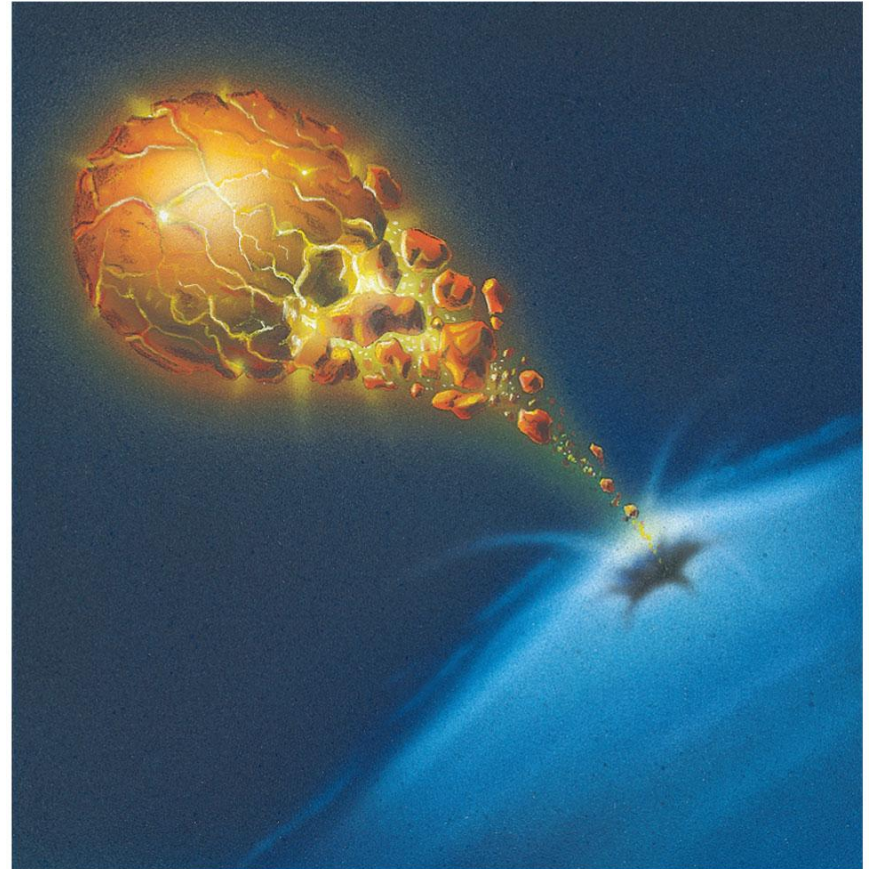
Taking the speed of light to be constant leads to some counterintuitive effects—length contraction, time dilation, the relativity of simultaneity, and the mass equivalent of energy.

# 22.7 Space Travel Near Black Holes

The gravitational effects of a black hole are unnoticeable outside of a few Schwarzschild radii—black holes do not “suck in” material any more than an extended mass would.

# 22.7 Space Travel Near Black Holes

Matter encountering a black hole will experience enormous tidal forces that will both heat it enough to radiate, and tear it apart:



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# 22.7 Space Travel Near Black Holes

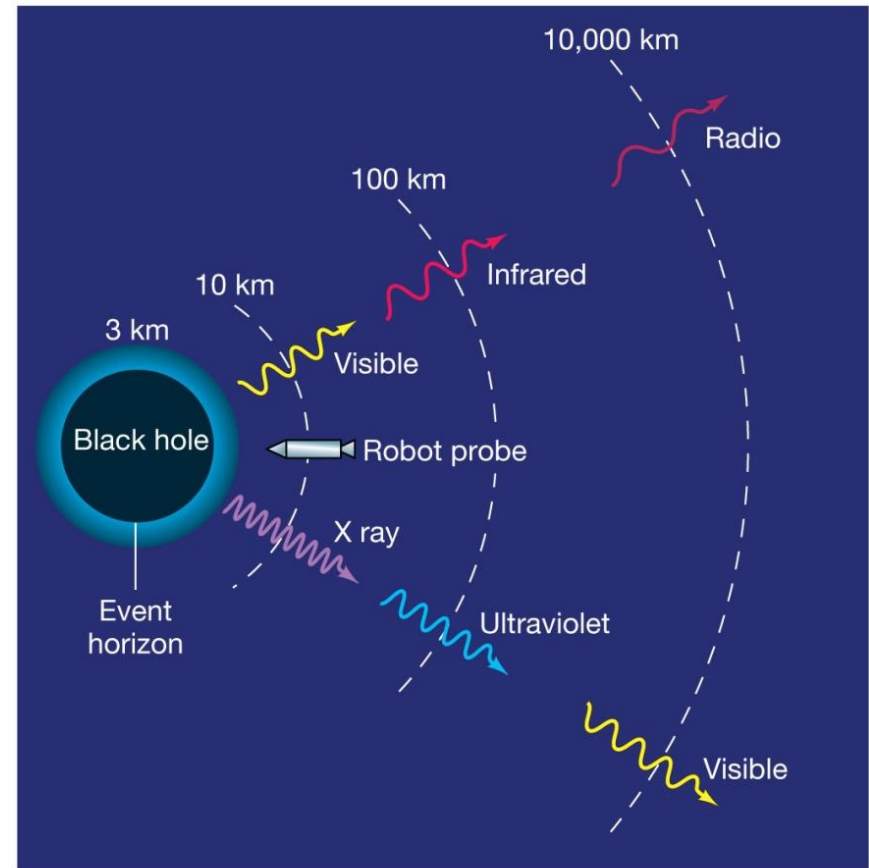
A probe nearing the event horizon of a black hole will be seen by observers as experiencing a dramatic redshift as it gets closer, so that time appears to be going more and more slowly as it approaches the event horizon.

This is called a gravitational redshift—it is not due to motion, but to the large gravitational fields present.

The probe, however, does not experience any such shifts; time would appear normal to anyone inside.

# 22.7 Space Travel Near Black Holes (cont.)

Similarly, a photon escaping from the vicinity of a black hole will use up a lot of energy doing so; it cannot slow down, but its wavelength gets longer and longer



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# 22.7 Space Travel Near Black Holes

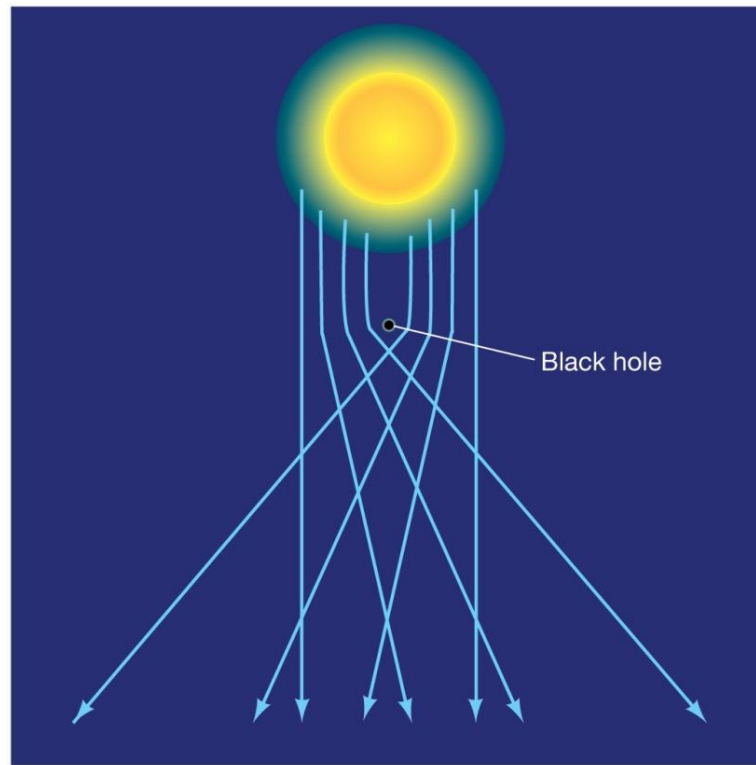
What's inside a black hole?

No one knows, of course; present theory predicts that the mass collapses until its radius is zero and its density is infinite, but it is unlikely that this actually happens.

Until we learn more about what happens in such extreme conditions, the interiors of black holes will remain a mystery.

# 22.8 Observational Evidence for Black Holes

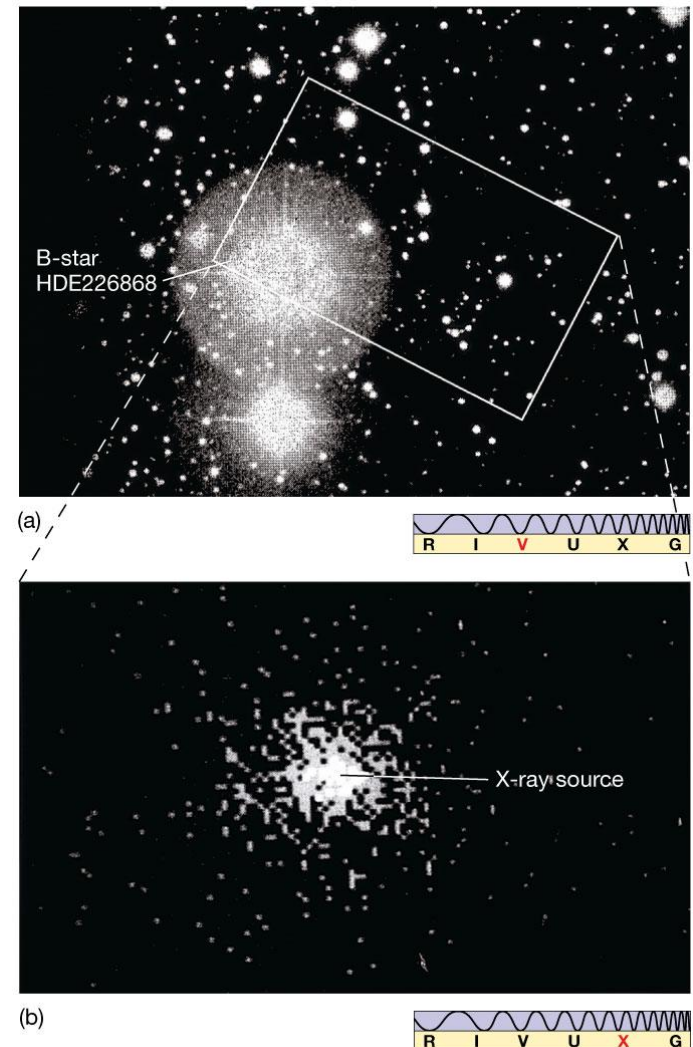
Black holes cannot be observed directly, as their gravitational fields will cause light to bend around them.



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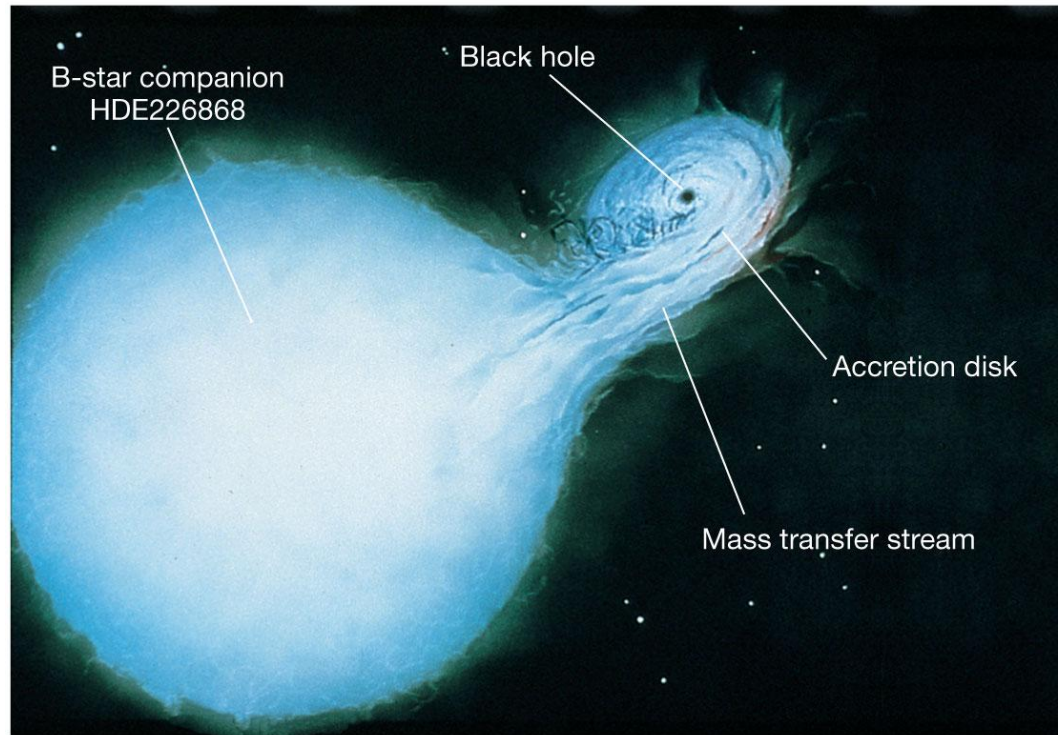
# 22.8 Observational Evidence for Black Holes

This bright star has an unseen companion that is a strong X-ray emitter called Cygnus X-1, which is thought to be a black hole:



# 22.8 Observational Evidence for Black Holes

The existence of black-hole binary partners for ordinary stars can be inferred by the effect the holes have on the star's orbit, or by radiation from infalling matter.



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# 22.8 Observational Evidence for Black Holes

Cygnus X-1 is a very strong black-hole candidate:

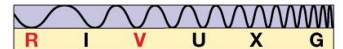
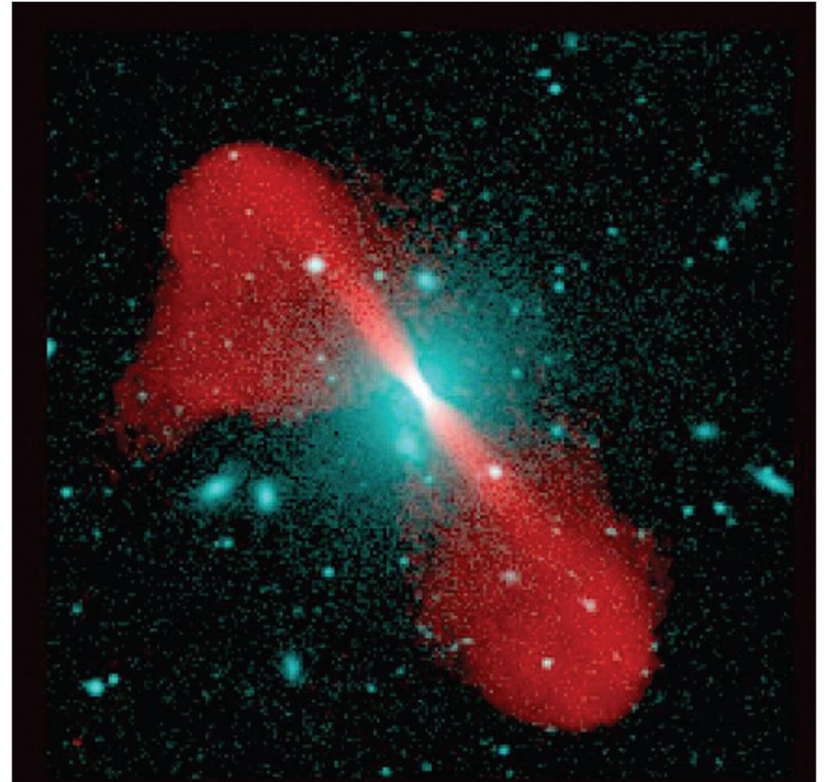
- Its visible partner is about 25 solar masses.
- The system's total mass is about 35 solar masses, so the X-ray source must be about 10 solar masses.
- Hot gas appears to be flowing from the visible star to an unseen companion.
- Short time-scale variations indicate that the source must be very small.



# 22.8 Observational Evidence for Black Holes

There are several other black-hole candidates as well, with characteristics similar to those of Cygnus X-1.

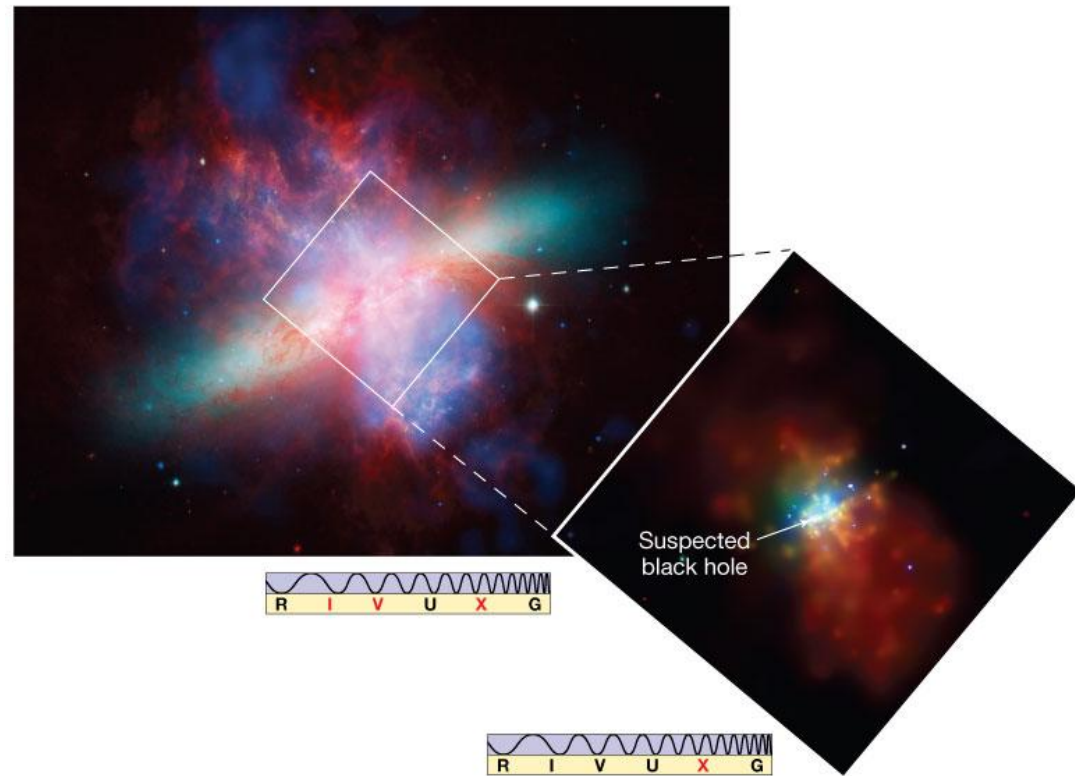
The centers of many galaxies contain supermassive black holes—about 1 million solar masses.



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# 22.8 Observational Evidence for Black Holes

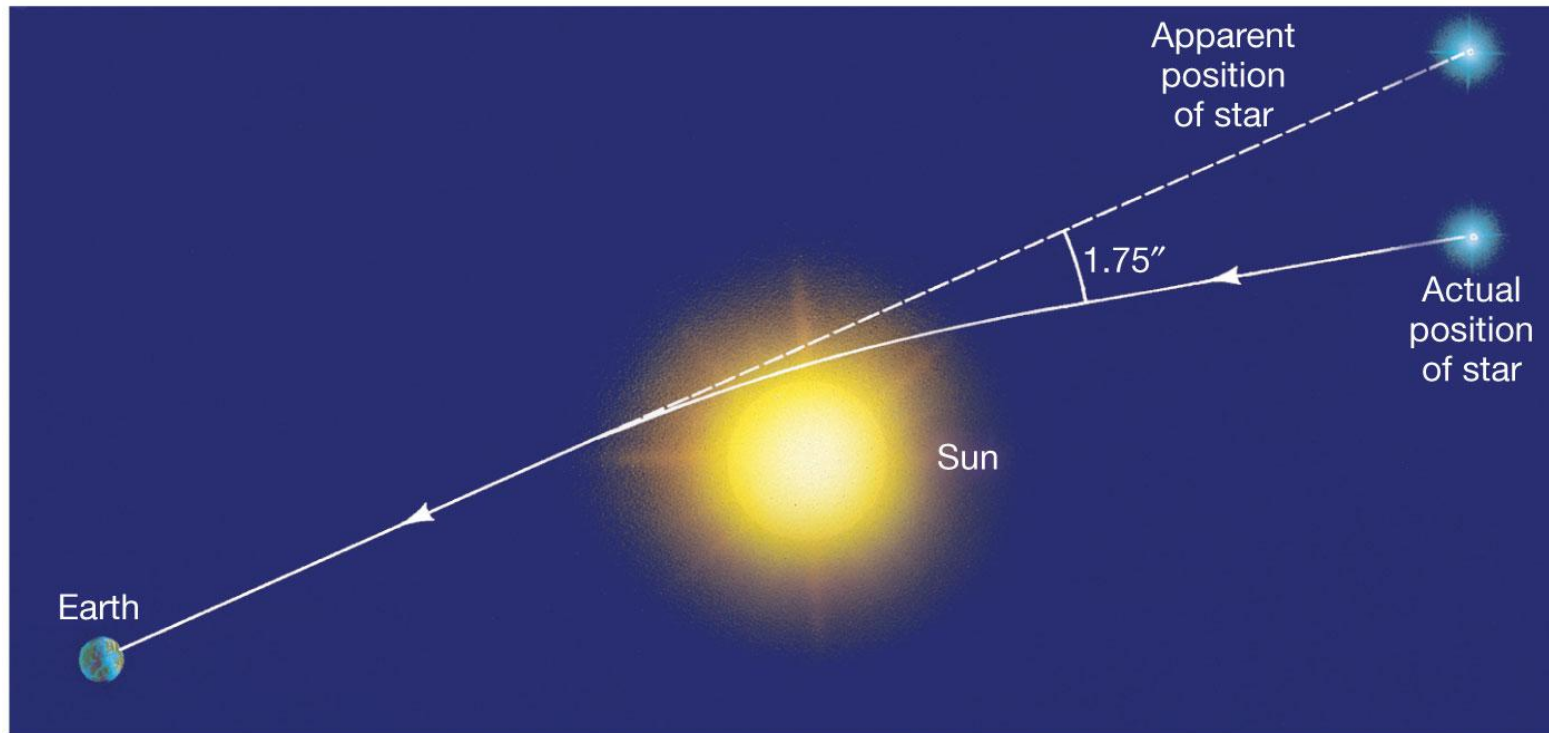
Recently, evidence for intermediate-mass black holes has been found; these are about 100 to 1000 solar masses. Their origin is not well understood.



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# More Precisely 22-1: Tests of General Relativity

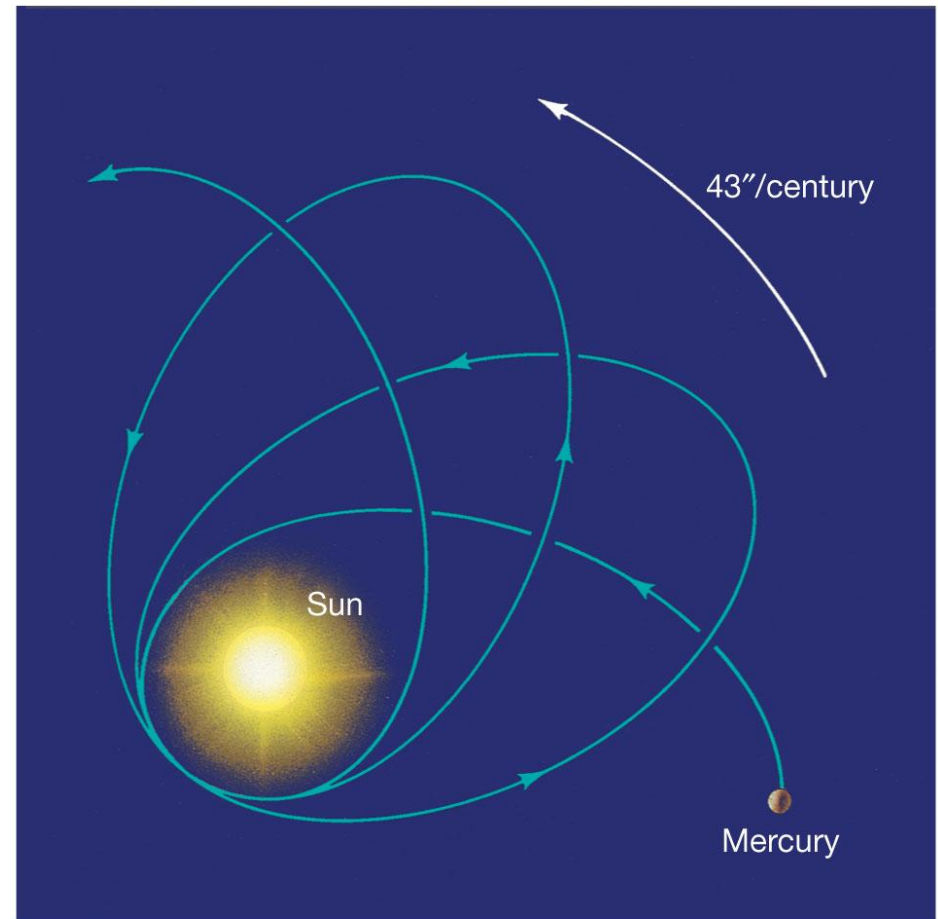
Deflection of starlight by the sun's gravity was measured during the solar eclipse of 1919; the results agreed with the predictions of general relativity.



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# More Precisely 22-1: Tests of General Relativity

Another prediction—the orbit of Mercury should precess due to general relativistic effects near the Sun; again, the measurement agreed with the prediction.



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# Discovery 22-1: Gravity Waves: A New Window on the Universe

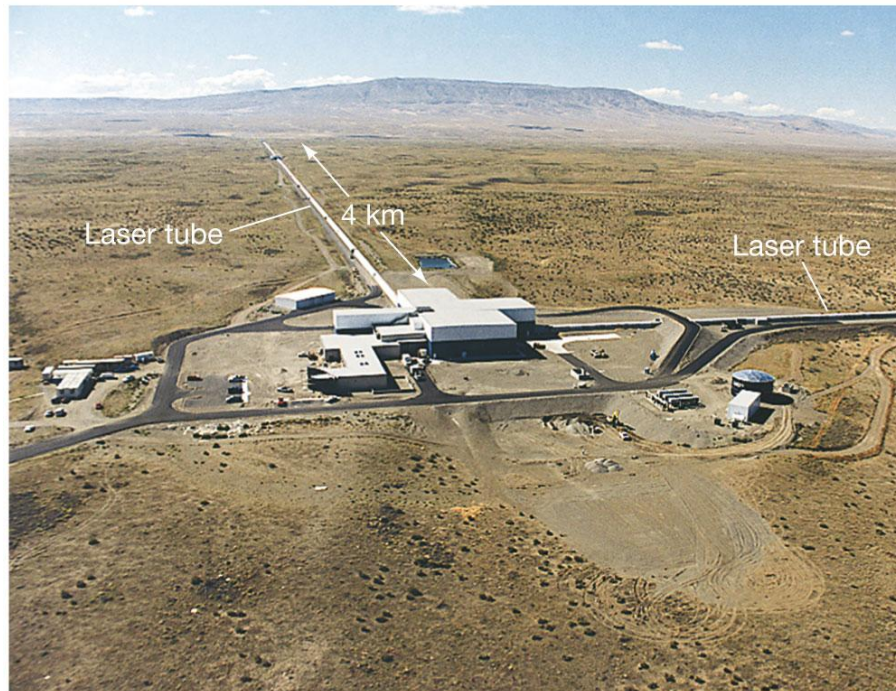
General relativity predicts that orbiting objects should lose energy by emitting gravitational radiation. The amount of energy is tiny, and these waves have not yet been observed directly.

However, a neutron-star binary system has been observed (two neutron stars); the orbits of the stars are slowing at just the rate predicted if gravity waves are carrying off the lost energy.



# Discovery 22-1: Gravity Waves: A New Window on the Universe

This figure shows LIGO, the Laser Interferometric Gravity-wave Observatory, designed to detect gravitational waves. It has been operating since 2003, but no waves have been detected yet.



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# Summary of Chapter 22

- Supernova may leave behind a neutron star.
- Neutron stars are very dense, spin rapidly, and have intense magnetic fields.
- Neutron stars may appear as pulsars due to the lighthouse effect.
- A neutron star in a close binary may become an X-ray burster or a millisecond pulsar.
- Gamma-ray bursts are probably due to two neutron stars colliding or hypernova.

# Summary of Chapter 22 (cont.)

- If core remnant is more than about 3 solar masses, it collapses into black hole.
- We need general relativity to describe black holes; it describes gravity as the warping of spacetime.
- Anything entering within the event horizon of a black hole cannot escape.
- The distance from the event horizon to the singularity is called the Schwarzschild radius.

# Summary of Chapter 22 (cont.)

- A distant observer would see an object entering black hole subject to extreme gravitational redshift and time dilation.
- Material approaching a black hole will emit strong X-rays.
- A few such X-ray sources have been found and are black-hole candidates.