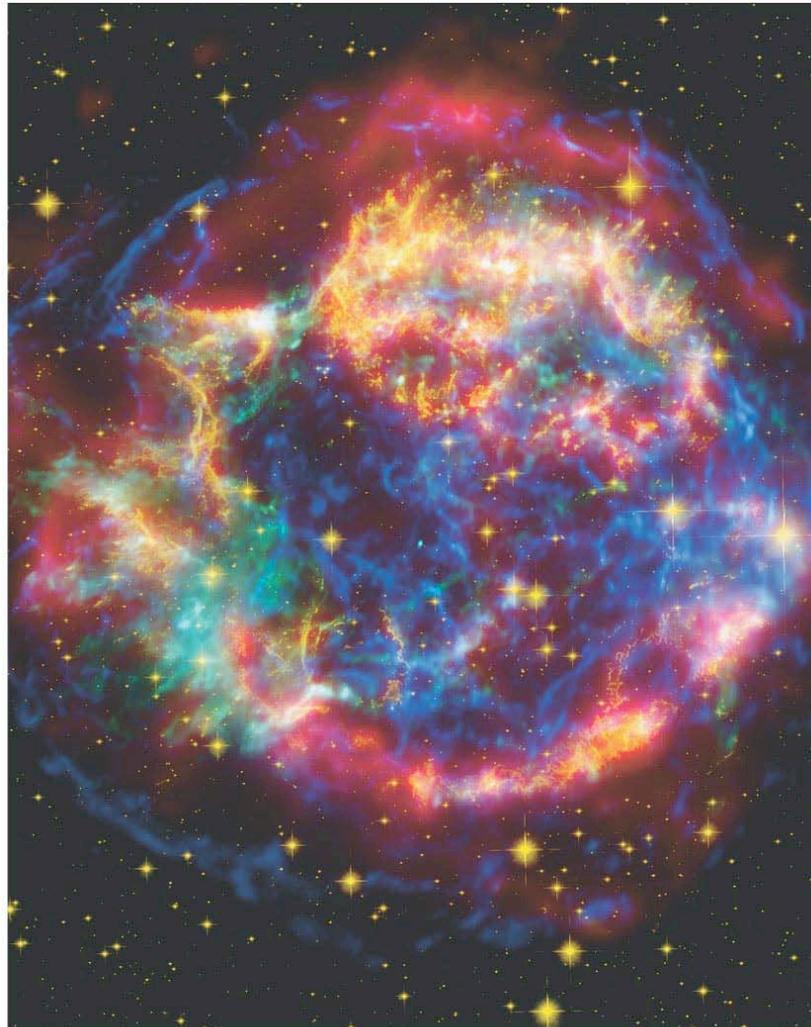


Chapter 22

Neutron Stars and Black Holes



Units of Chapter 22

22.1 Neutron Stars

22.2 Pulsars

22.3 Neutron-Star Binaries: X-ray bursters

[Look at the three slides and the pictures in your book, but I won't test you on this in detail, and we may skip altogether in class.]

22.4 Gamma-Ray Bursts

22.5 Black Holes

22.6 Einstein's Theories of Relativity

Special Relativity

22.7 Space Travel Near Black Holes

22.8 Observational Evidence for Black Holes

Tests of General Relativity

Gravity Waves: A New Window on the Universe

Neutron Stars and Pulsars

22.1 Neutron Stars

According to models for stellar explosions:

After a **carbon detonation supernova** (white dwarf in binary), little or nothing remains of the original star.

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

[Recall that during core collapse the iron core (ashes of previous fusion reactions) is disintegrated into protons and neutrons, the protons combine with the surrounding electrons to make more neutrons, so the core becomes pure neutron matter. Because of this, core collapse can be halted if the core's mass is between 1.4 (the Chandrasekhar limit) and about 3-4 solar masses, by neutron degeneracy.]

What do you get if the core mass is less than 1.4 solar masses?

Greater than 3-4 solar masses?

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**:



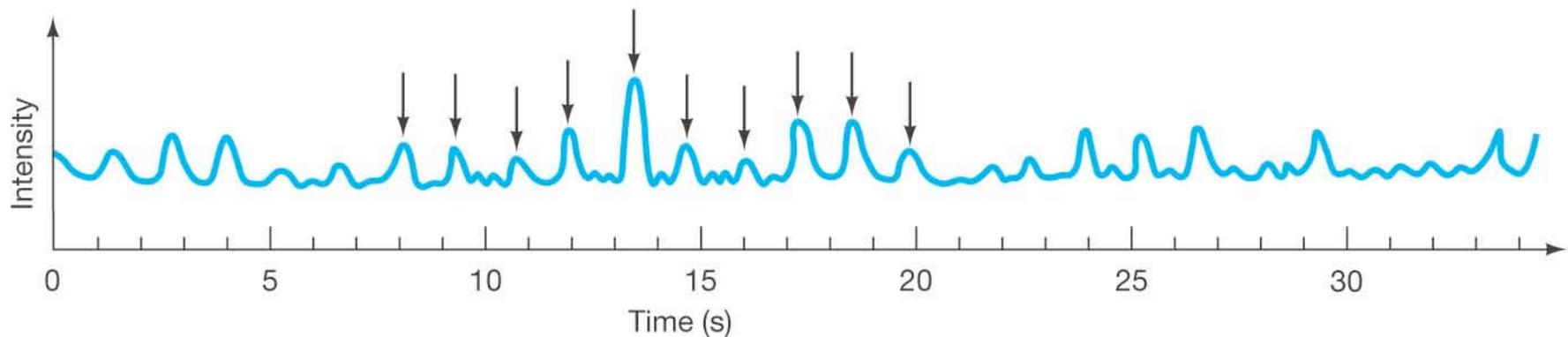
Other important properties of neutron stars (beyond mass and size):

- **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 (could it be pulsation? An extraterrestrial signal?), it was realized that this was a **neutron star**, spinning *very* rapidly.



Light curve of pulsar: notice precisely timed periodic pulses.

22.2 Pulsars

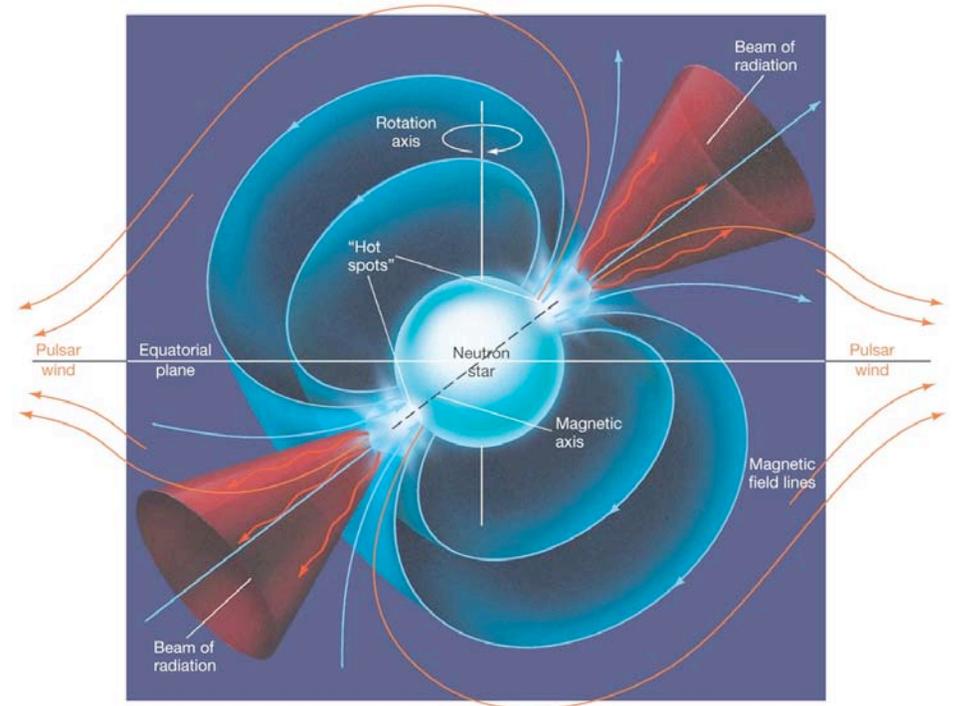
But why would a neutron star flash on and off?

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.

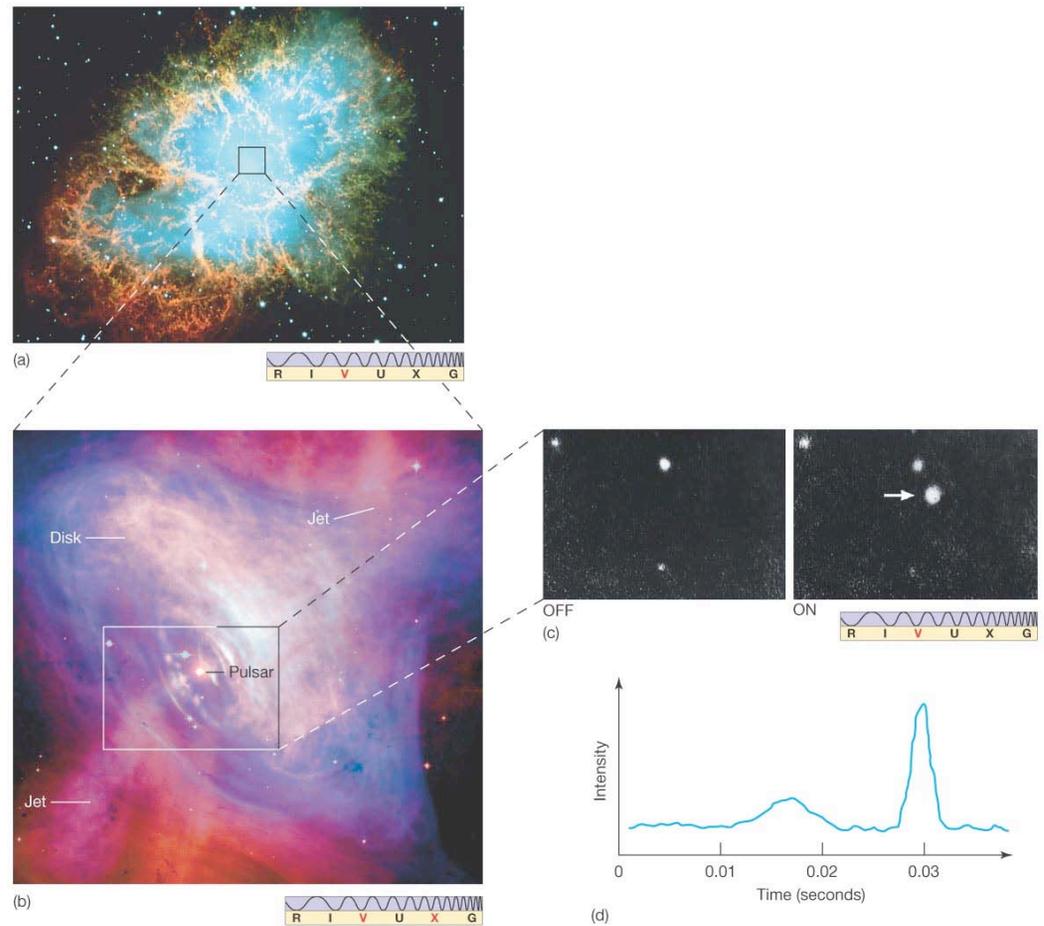
Pulsars radiate their energy away quite rapidly; the radiation weakens and stops in a few tens of millions of years, making the neutron star virtually undetectable.

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, which “blinks” about 30 times per second. The images show it in the “off” and “on” states. The disk and jets are also visible:

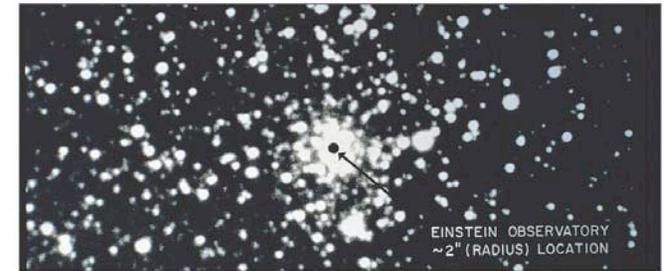
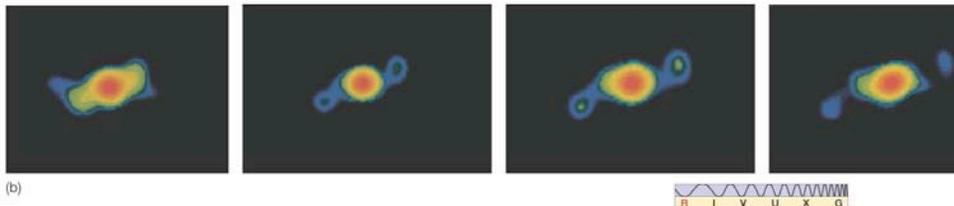
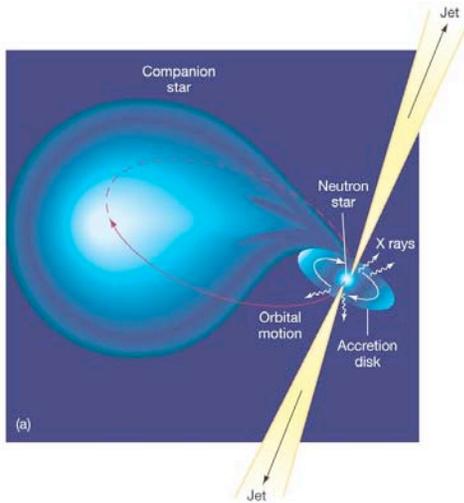


Neutron Star Binaries and X-ray bursters

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:

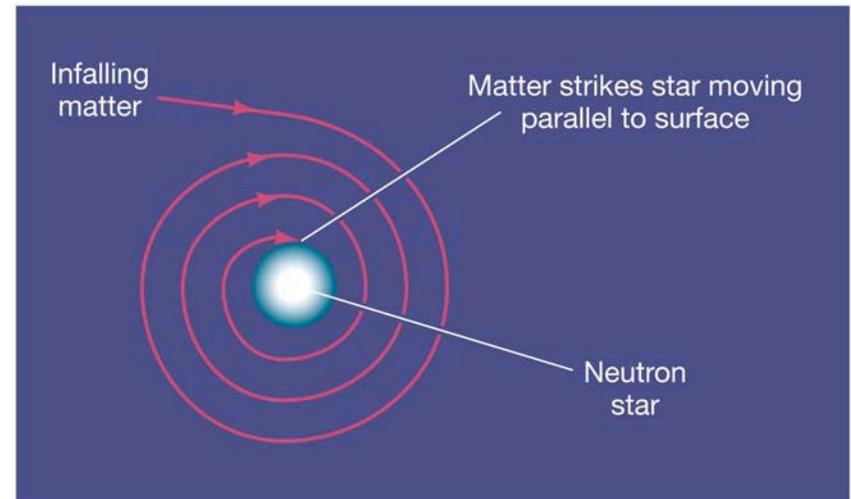
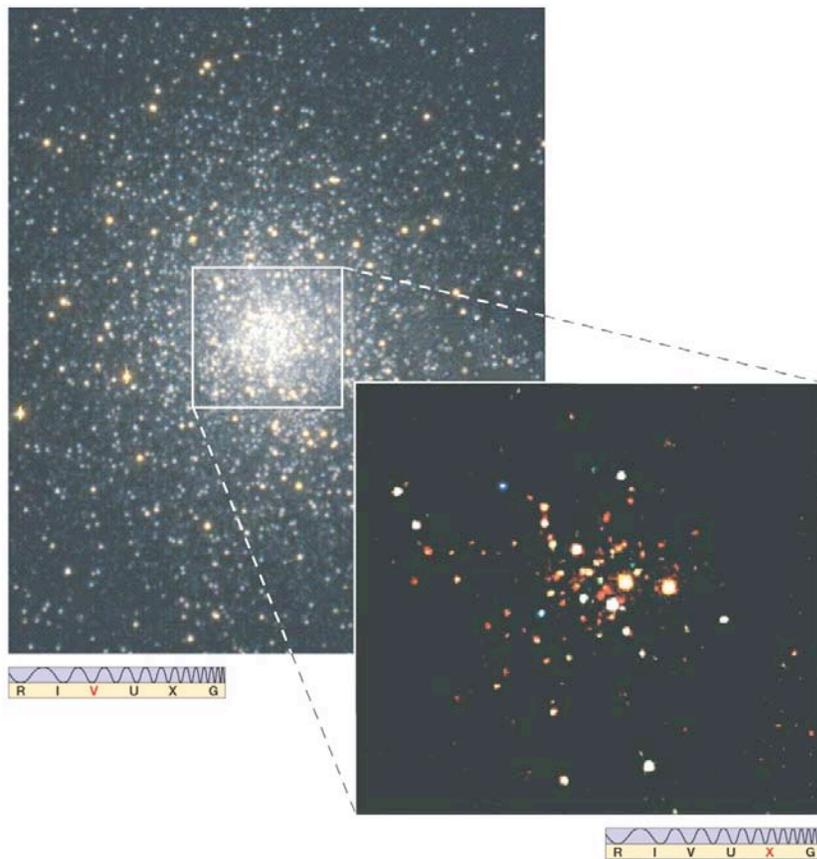
These X-ray bursts are thought to originate on neutron stars that have binary partners.



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.



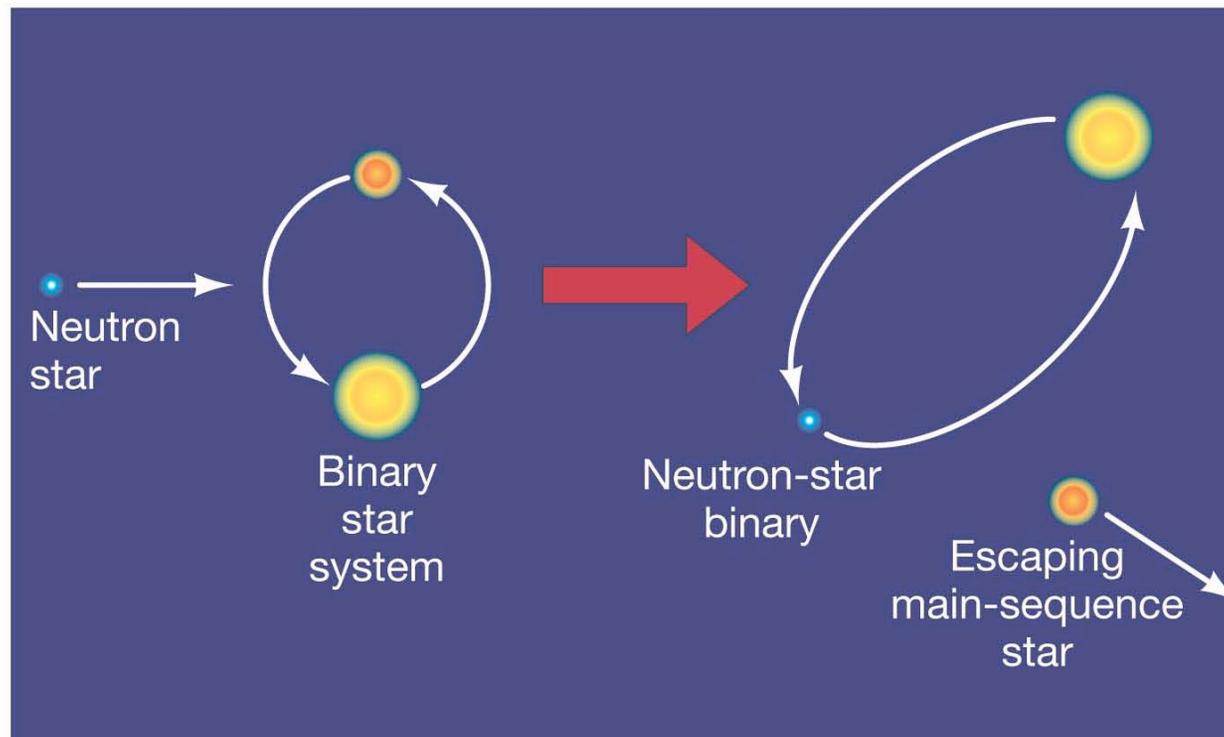
Millisecond pulsars are thought to be “spun-up” by matter falling in from a companion.

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

22.3 Neutron-Star Binaries

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

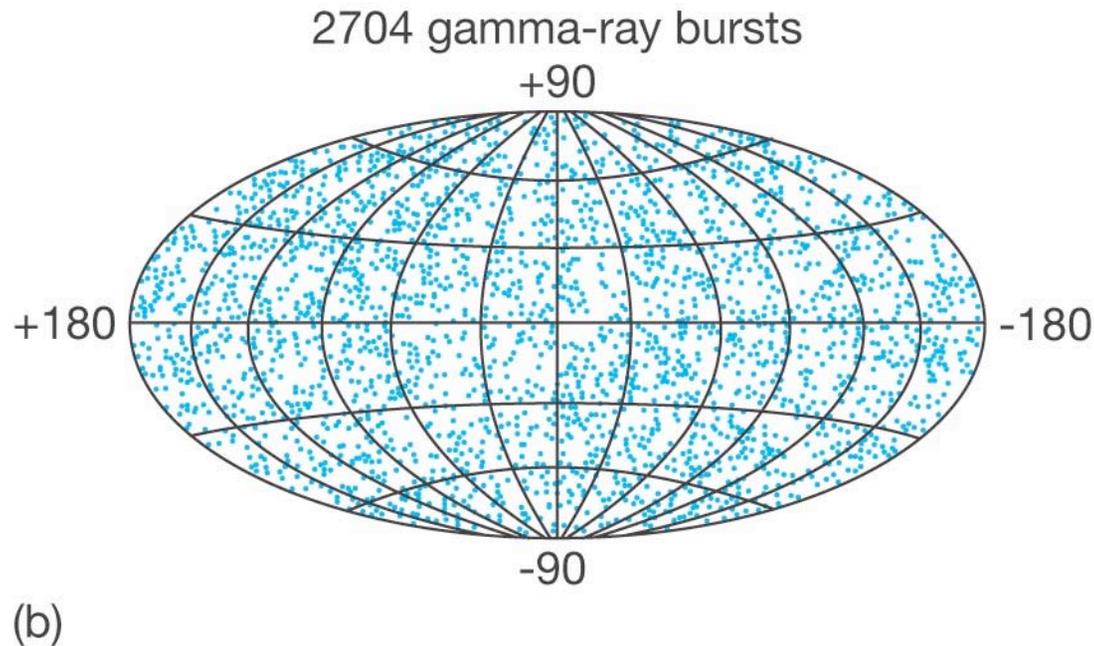
These variations were thought to be consistent with a planet, which must have been picked up by the neutron star. See diagram below.



Gamma-ray Bursts

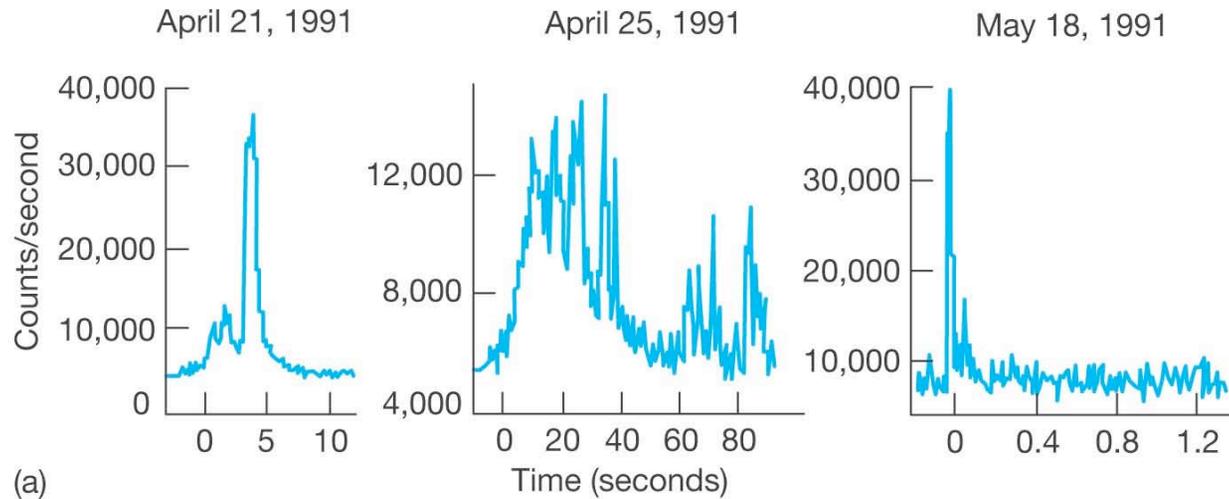
22.4 Gamma-Ray Bursts

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.



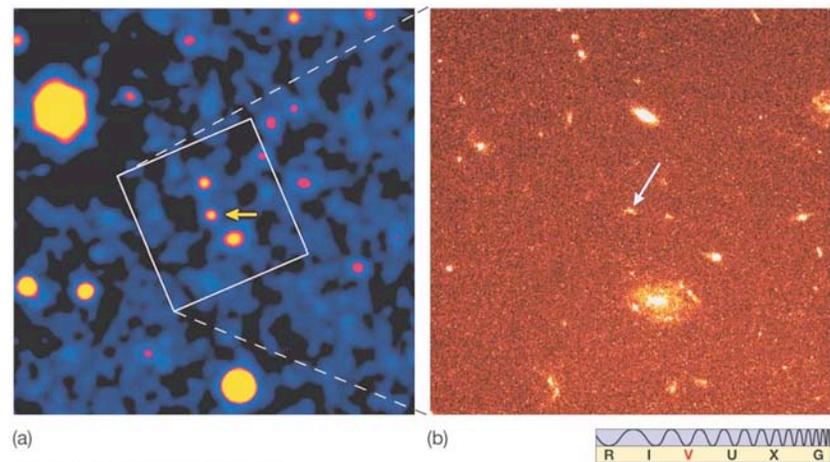
22.4 Gamma-Ray Bursts

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



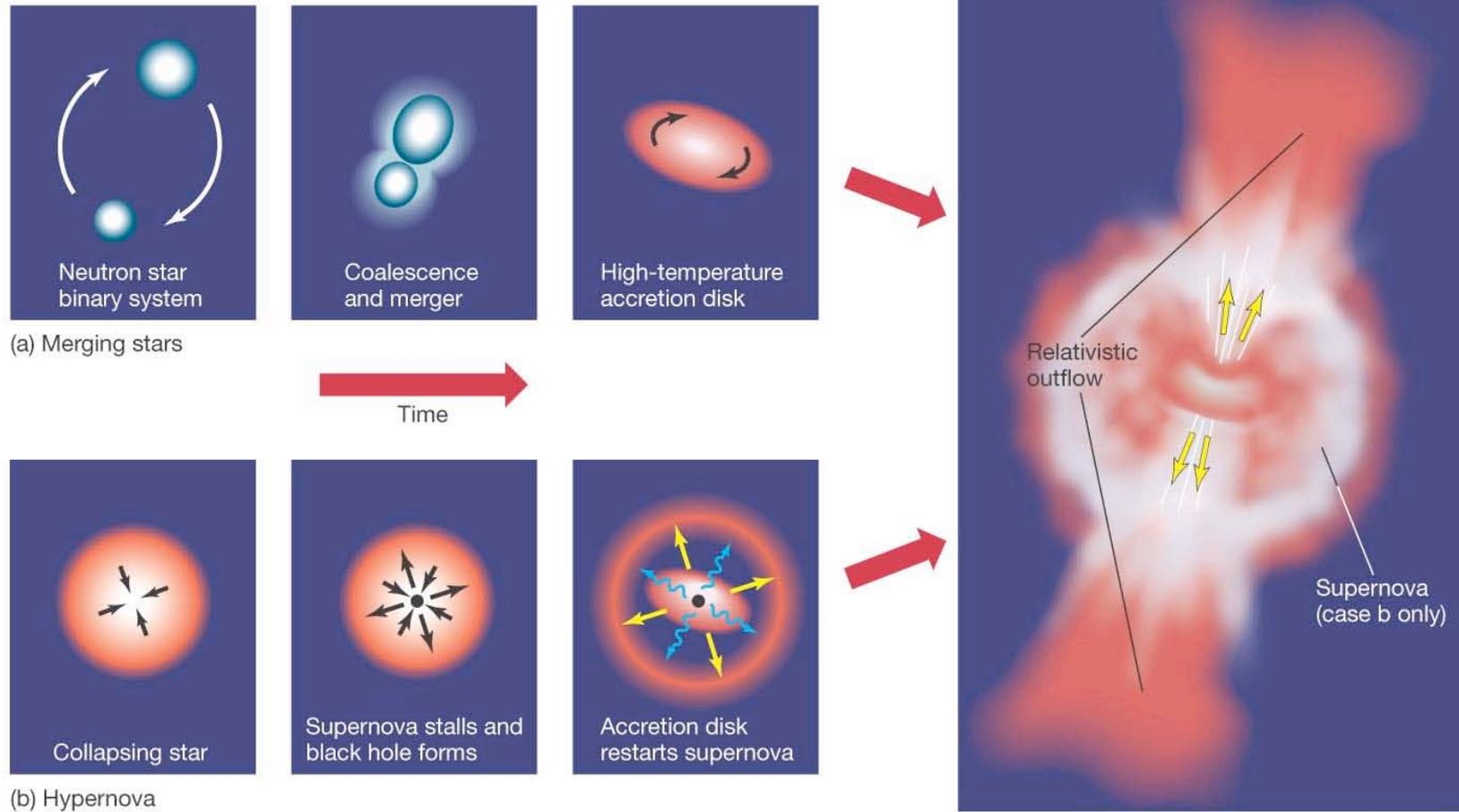
Distance measurements of some gamma bursts show them to be very far away—2 billion parsecs for the first one measured.

Occasionally the spectrum of a burst can be measured, allowing distance determination (using a method that will be explained in a later chapter.



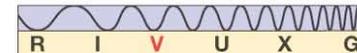
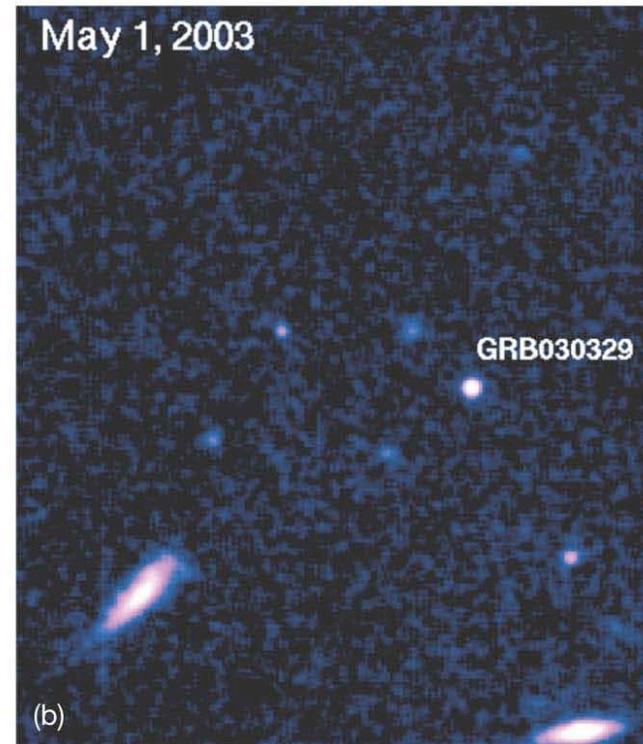
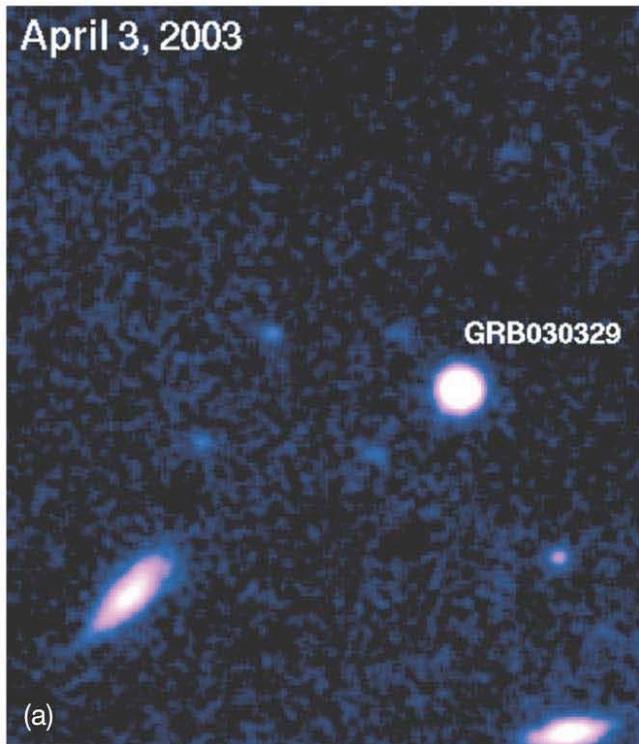
22.4 Gamma-Ray Bursts

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



22.4 Gamma-Ray Bursts

This burst had a light curve that looks very much like an exceptionally strong supernova, lending credence to the hypernova model:

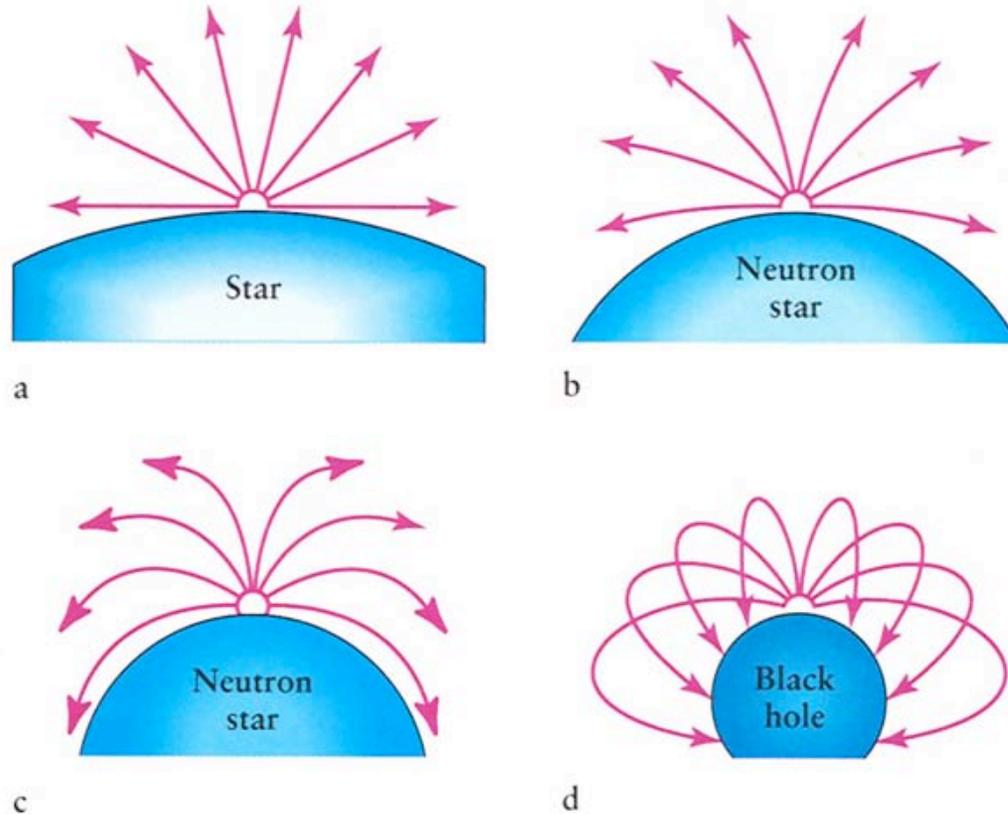


Black Holes

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.

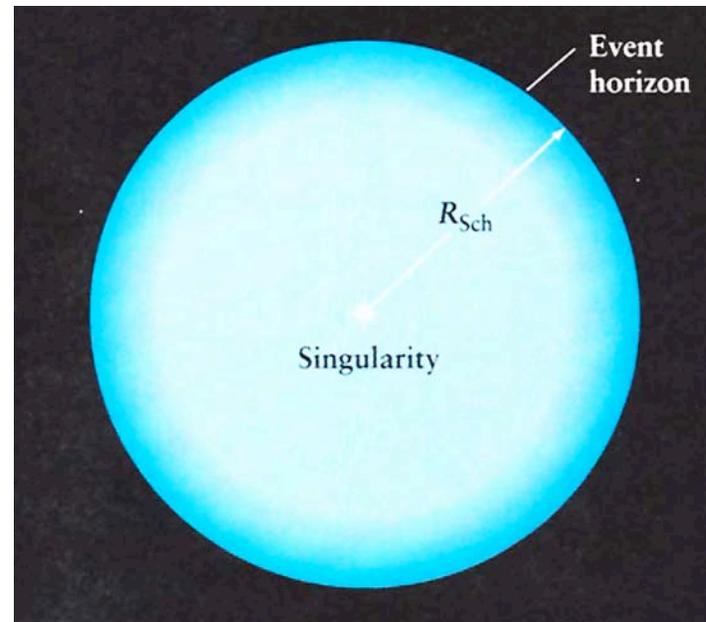


Black holes

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.

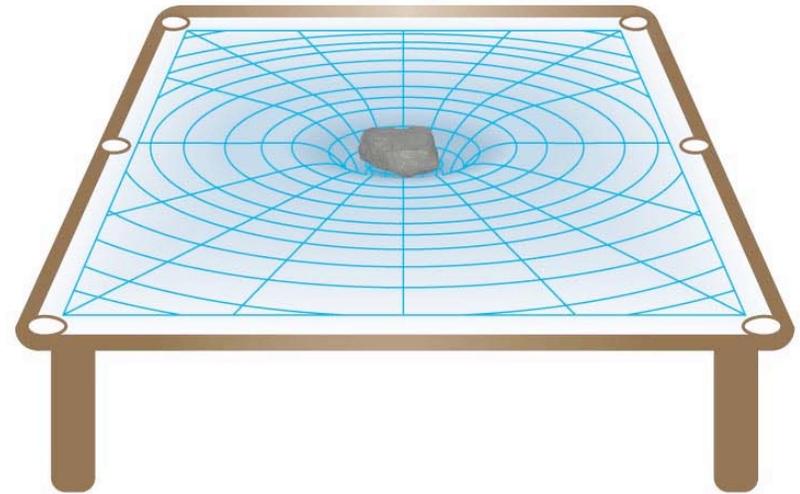
Once the black hole has collapsed, the Schwarzschild radius takes on another meaning—it is the event horizon. Nothing within the event horizon can escape the black hole.



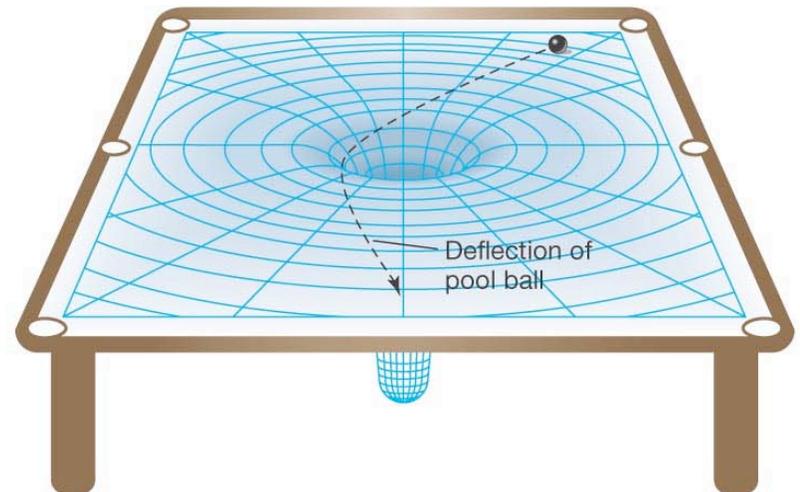
22.6 Einstein's Theories of Relativity

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.



(a)

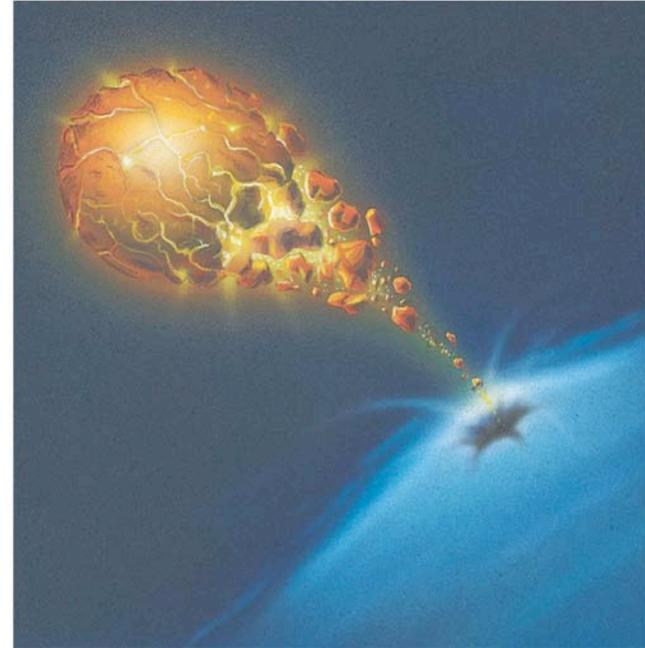


(b)

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.

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



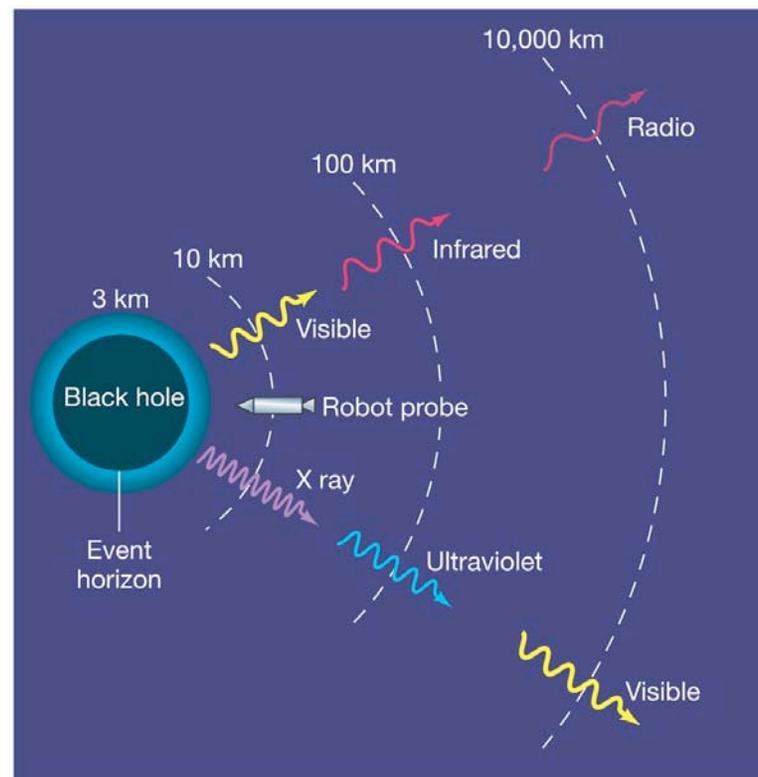
A probe nearing the event horizon of a black hole will be seen by observers as experiencing a dramatic redshift as it gets closer, so that time appears to be going more and more slowly as it approaches the event horizon.

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



22.7 Space Travel Near Black Holes

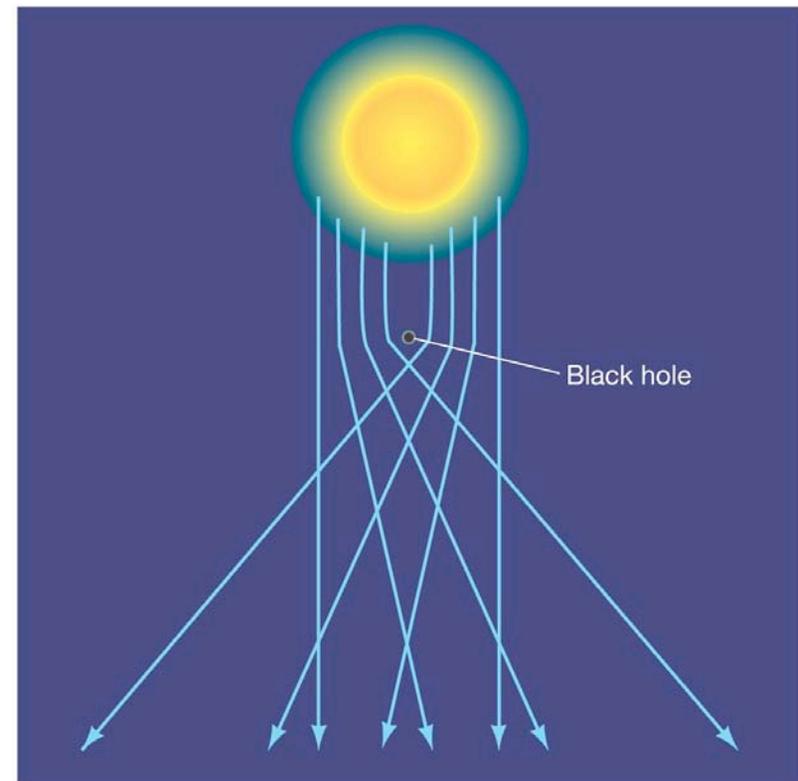
What's **inside** a black hole?

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. Our ignorance is due to the fact that the densities and temperatures in a black hole are so large that gravity and all the other forces should be unified as one--"quantum gravity." Physics has no theory for such a state.

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

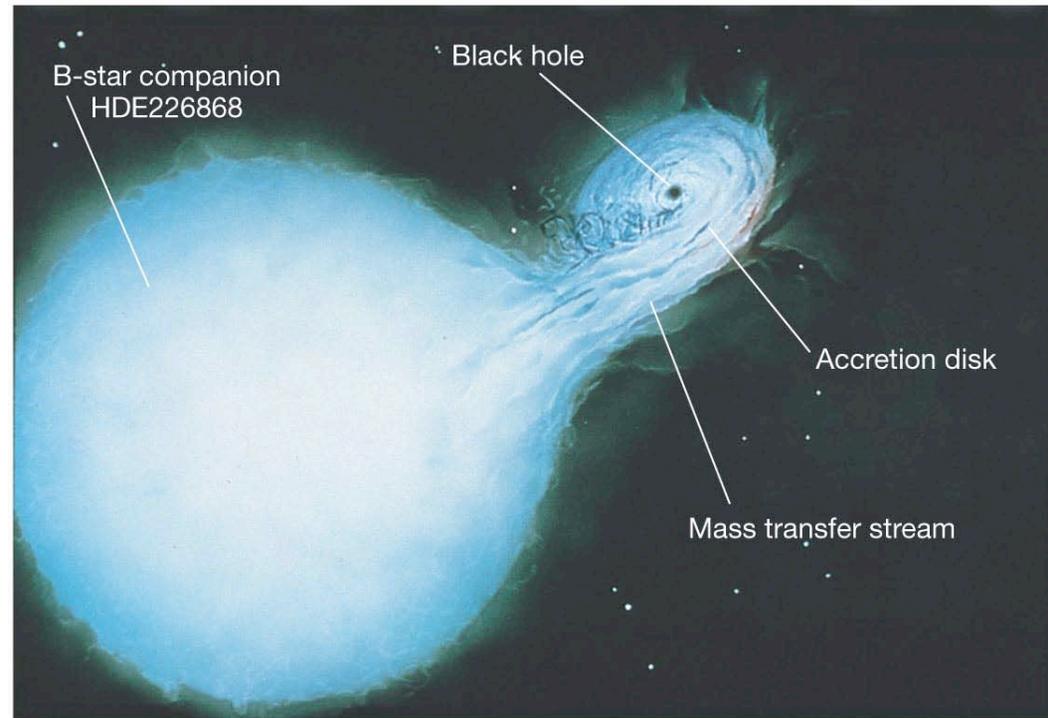
22.8 Observational Evidence for Black Holes

Black holes cannot be observed directly, as their gravitational fields will cause light to bend around them. Otherwise you could possibly see the black hole as a dot against the bright background star.



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. In the case shown, a giant B star is observed, using the Doppler effect, to be orbiting *something* that is too faint to be seen.



X-ray emission is also observed from the system, presumably an accretion disk around *some* kind of compact remnant.

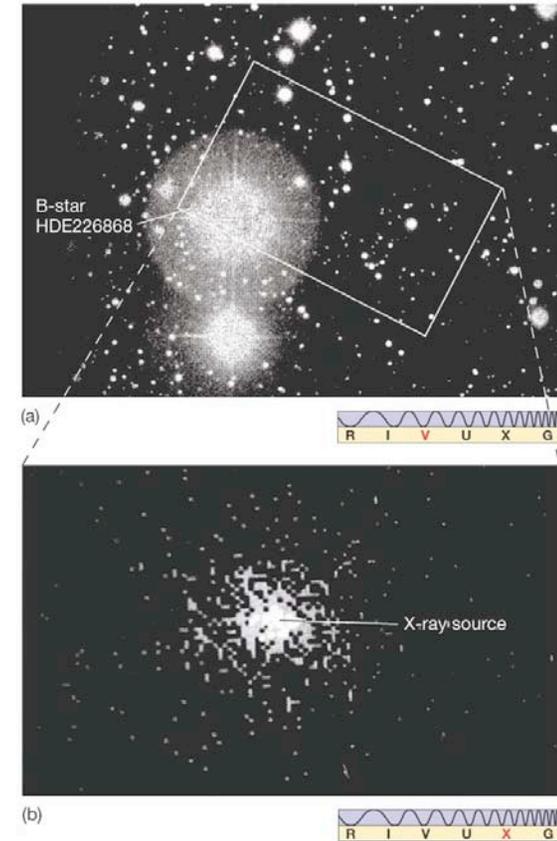
White dwarf? Neutron star? Black hole? Theoretically, the distinction should be the mass of the object. If larger than about 10 solar masses, the object should have too much gravity to become a white dwarf or a neutron star. Unfortunately it is difficult to obtain masses even for “normal” stars.

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.

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

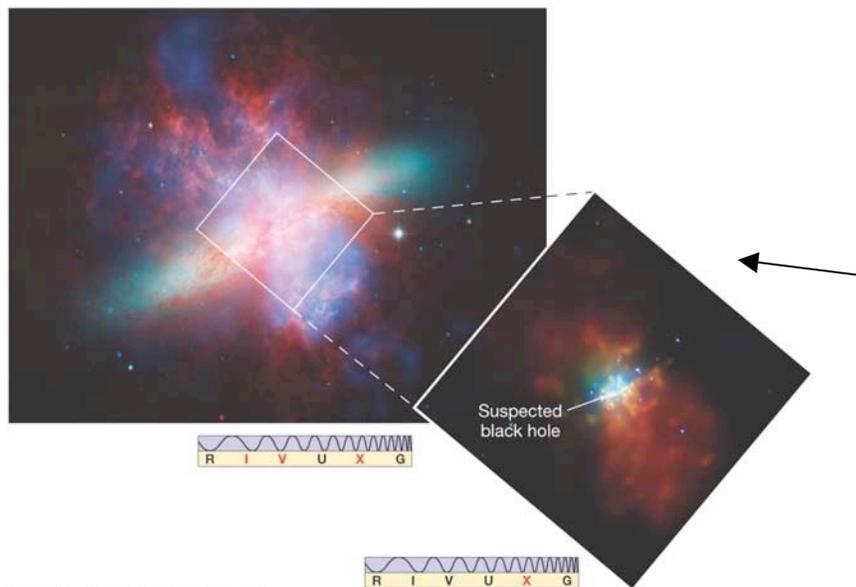
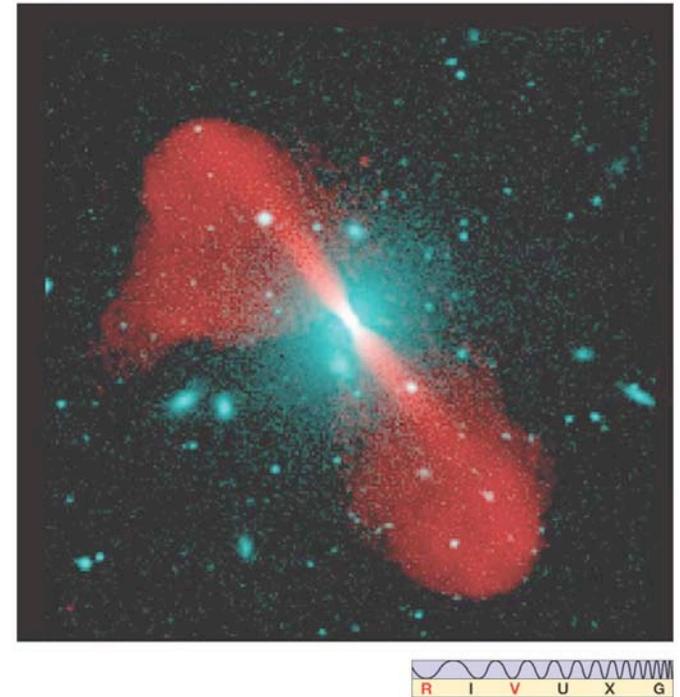
- Its visible partner is about **25 solar masses**.
- The system's total mass is about **35 solar masses**, so the X-ray source must be about **10 solar masses**.
- **Hot gas** appears to be flowing from the visible star to an unseen companion.
- **Short time-scale variations** indicate that the source 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 hole**—about 1 million solar masses.



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

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. However this is not a direct detection of gravity waves, which are the “holy grail” of relativity.

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.

That was two years ago...

Homework problem:

Has LIGO claimed a detection of gravity waves in the past two years?



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.
- 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.