Chapter 13
Neutron Stars and Black Holes

Units of Chapter 13

Neutron Stars

Pulsars

Neutron Star Binaries

Gamma-Ray Bursts

Black Holes

Einstein’s Theories of Relativity

Space Travel Near Black Holes

Observational Evidence for Black Holes

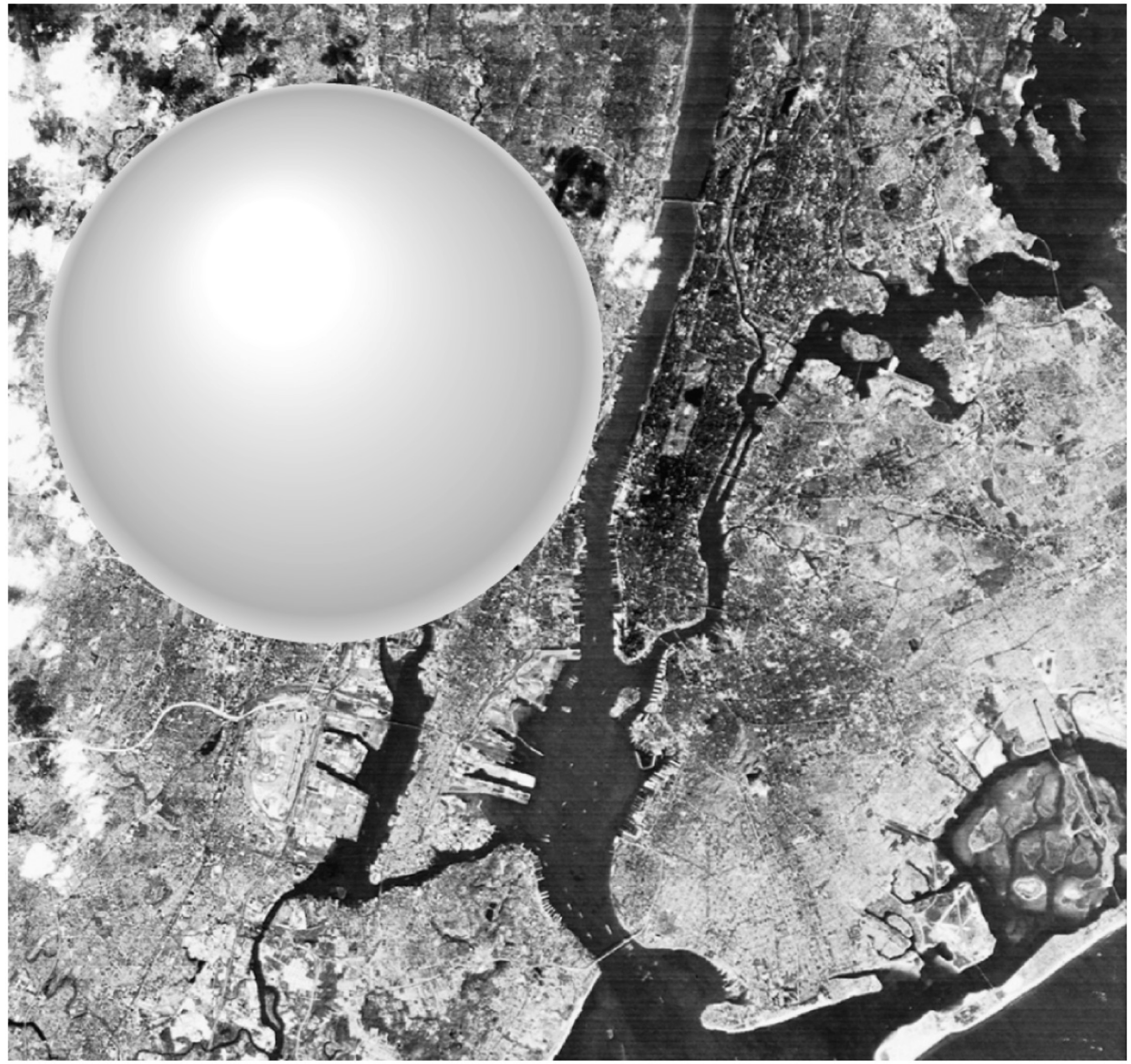
13.1 Neutron Stars

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.

13.1 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.



13.1 Neutron Stars

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

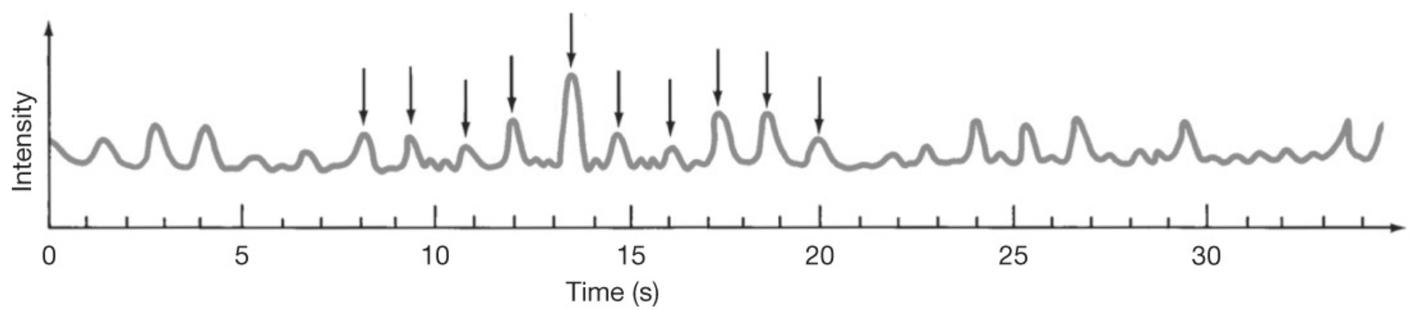
Rotation – as the parent star collapses, the neutron core spins very rapidly, conserving angular momentum. Typical periods are fractions of a second.

Magnetic field – again as a result of the collapse, the neutron star’s magnetic field becomes enormously strong.

13.2 Pulsars

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

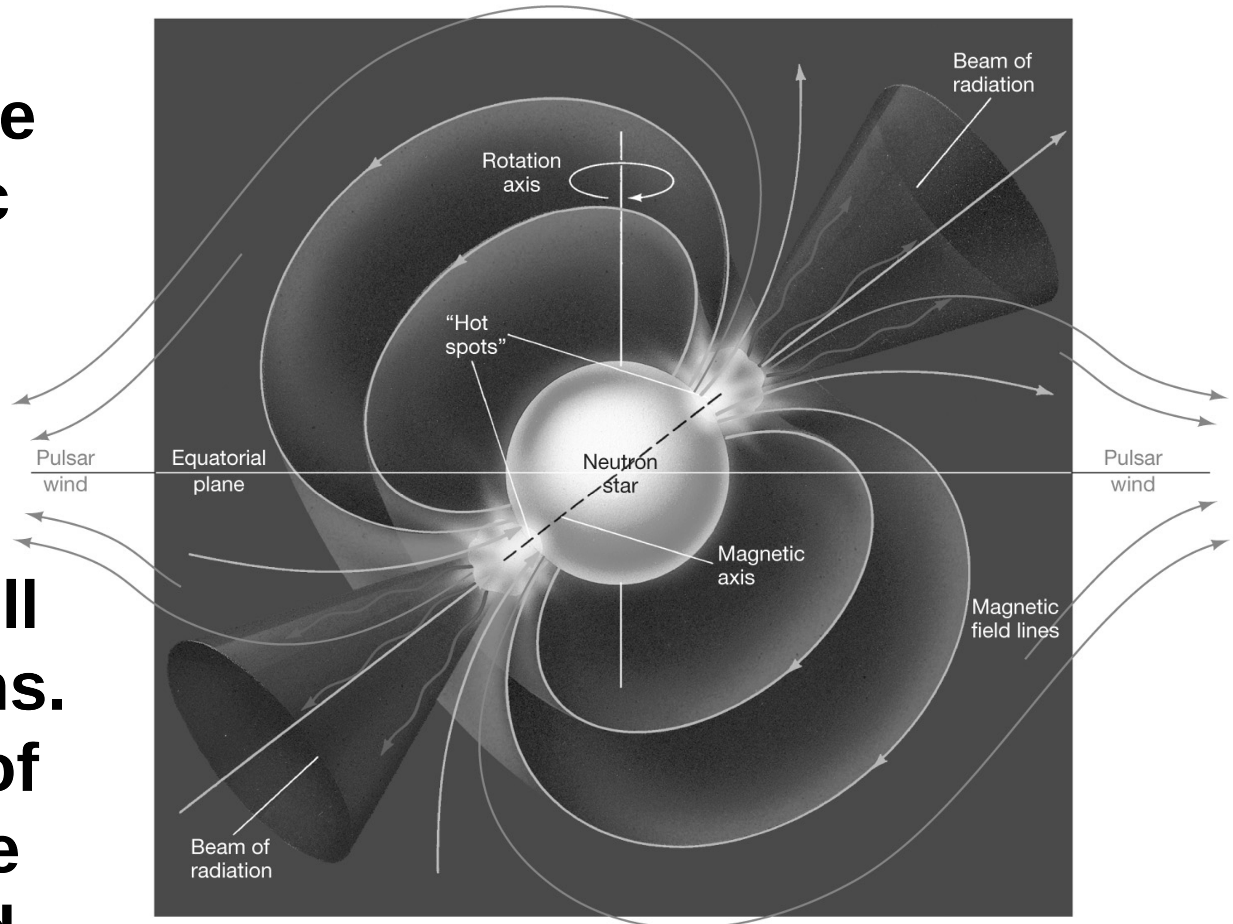
After some initial confusion, it was realized that this was a neutron star, spinning very rapidly.



13.2 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, as that is where they can escape. 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 blinking on and off.



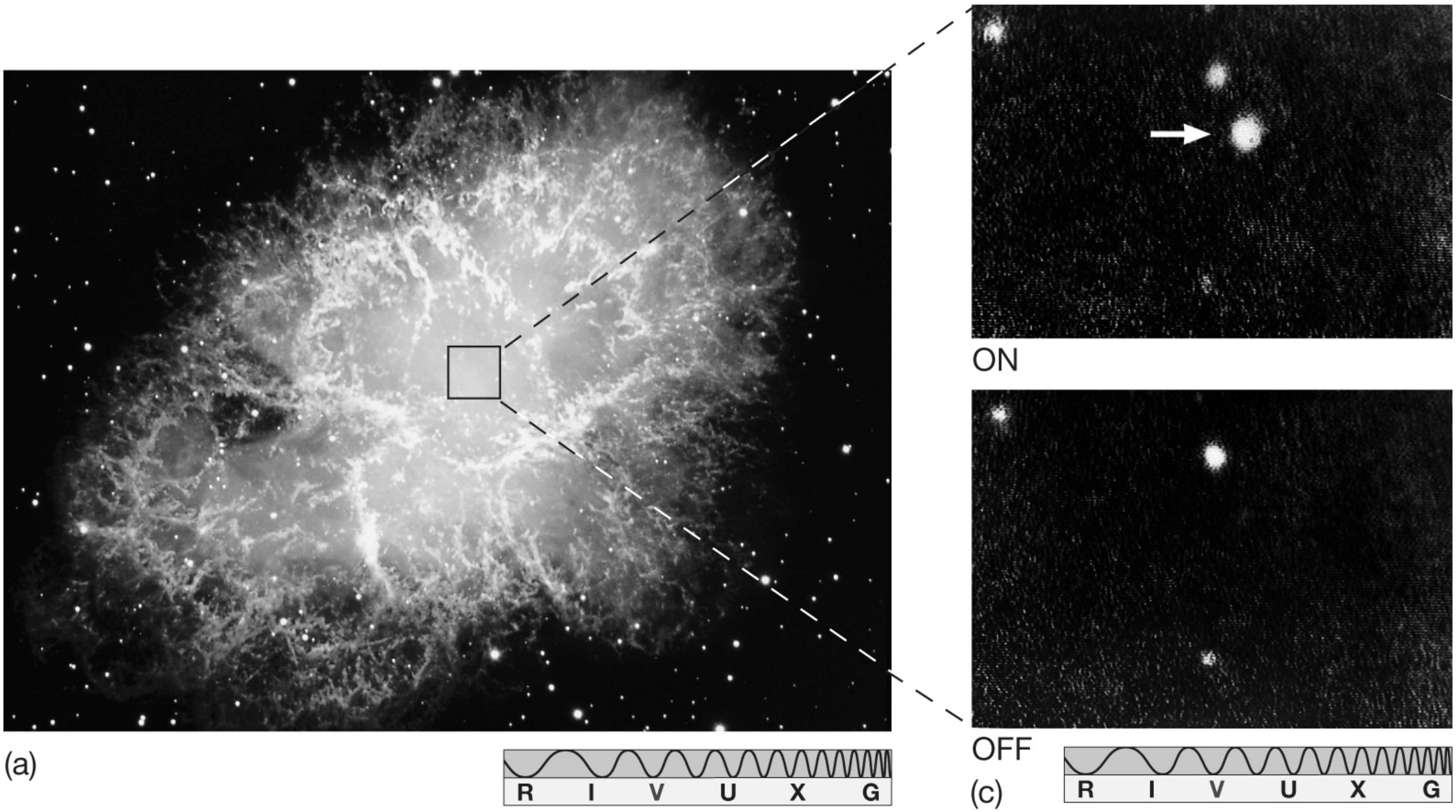
13.2 Pulsars

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.

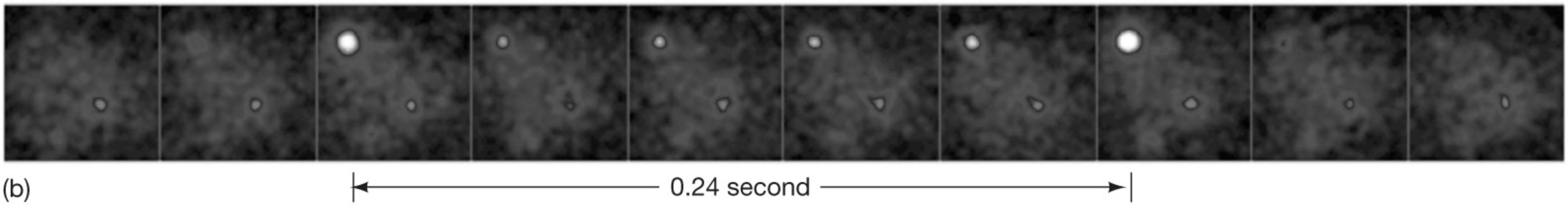
Pulsars also will not be visible on Earth if their jets are not pointing our way.

13.2 Pulsars

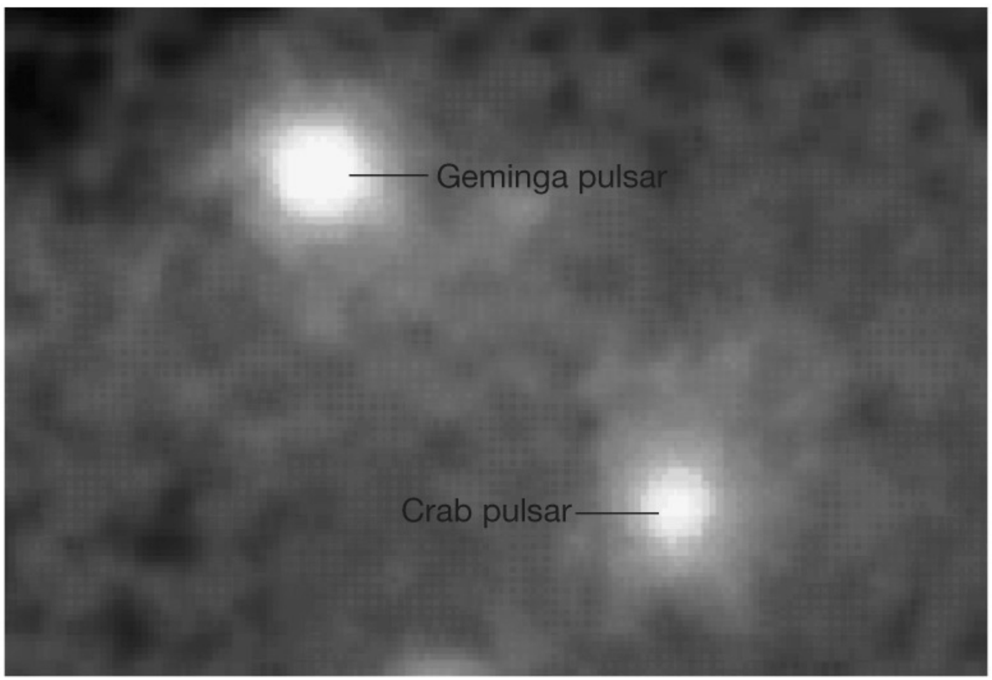
There is a pulsar at the center of the Crab Nebula; the images at right show it in the "off" and "on" positions.



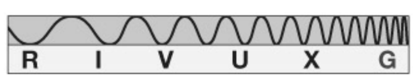
13.2 Pulsars



(b)



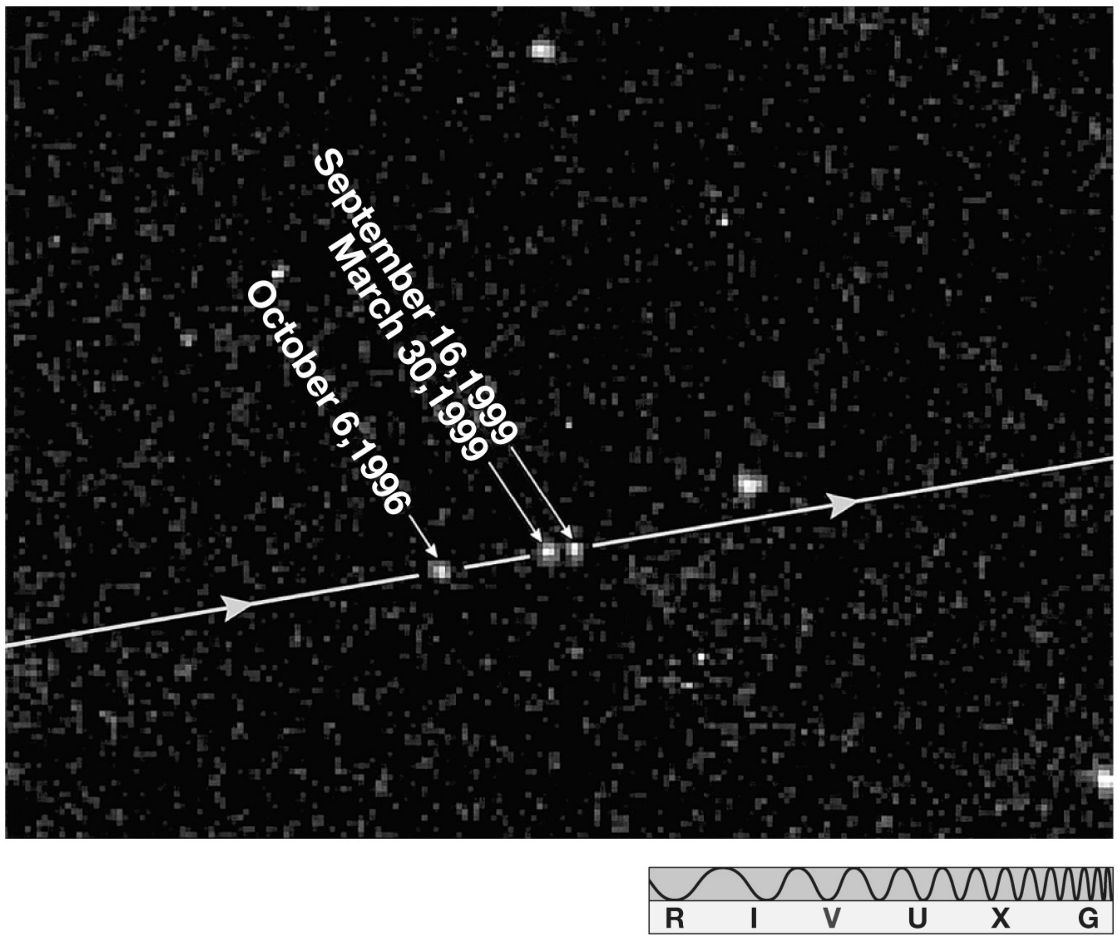
(a)



The Crab pulsar also pulses in the gamma ray spectrum, as does the nearby Geminga pulsar.

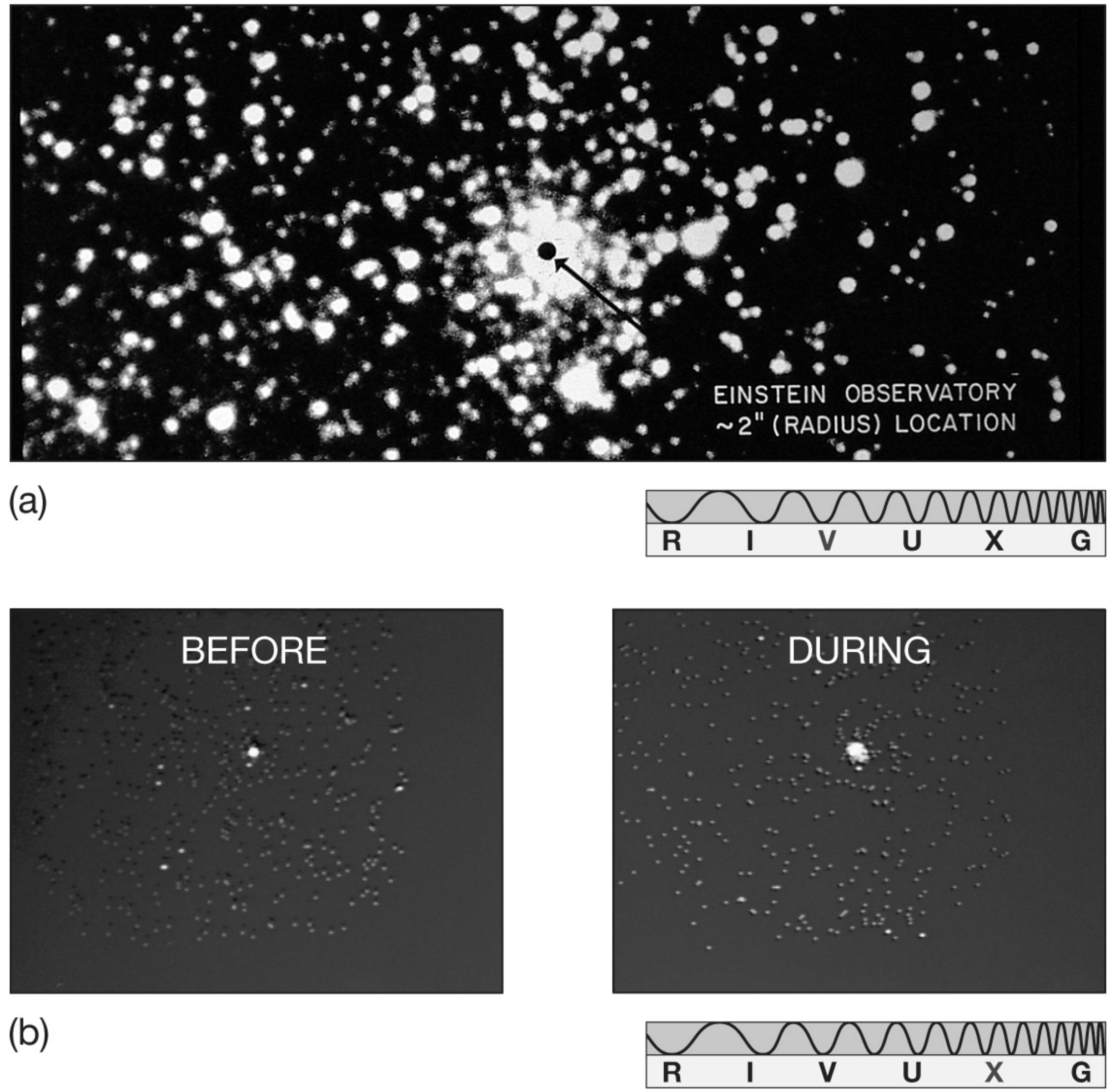
13.2 Pulsars

An isolated neutron star has been observed by the Hubble telescope; it is moving rapidly, has a surface temperature of 700,000 K, and is about 1 million years old.



13.3 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.



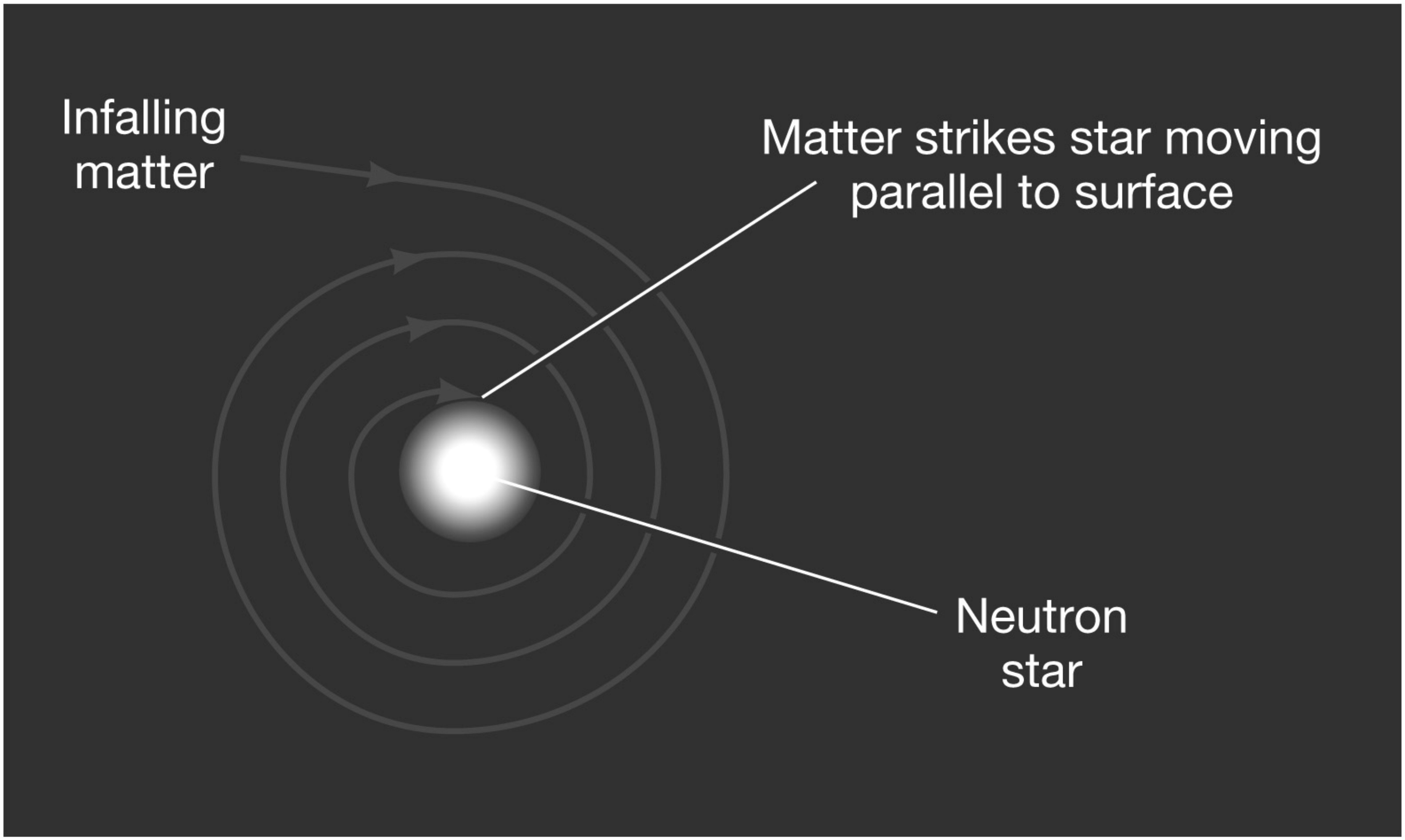
13.3 Neutron-Star Binaries

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

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

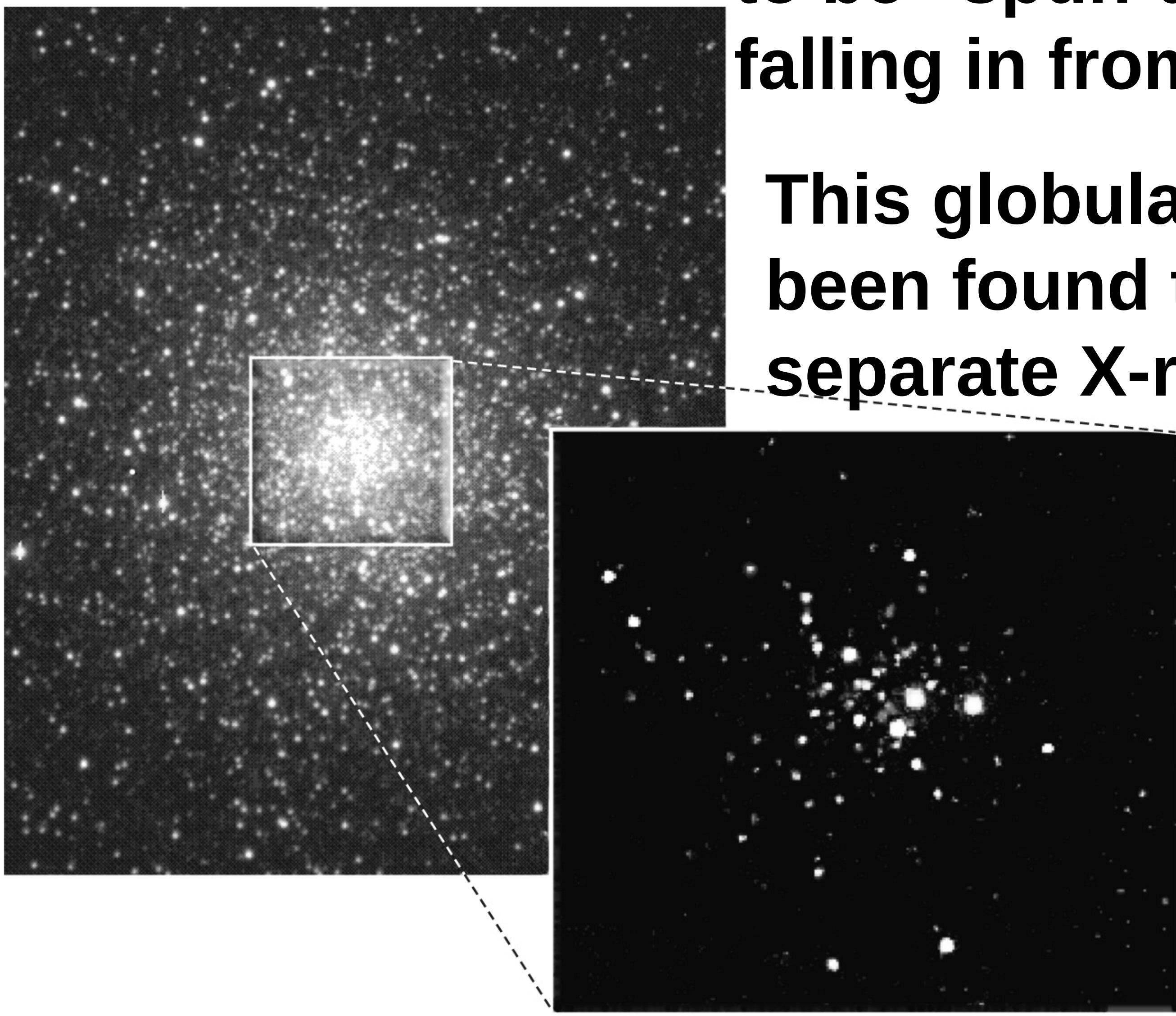
13.3 Neutron-Star Binaries

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.



13.3 Neutron-Star Binaries

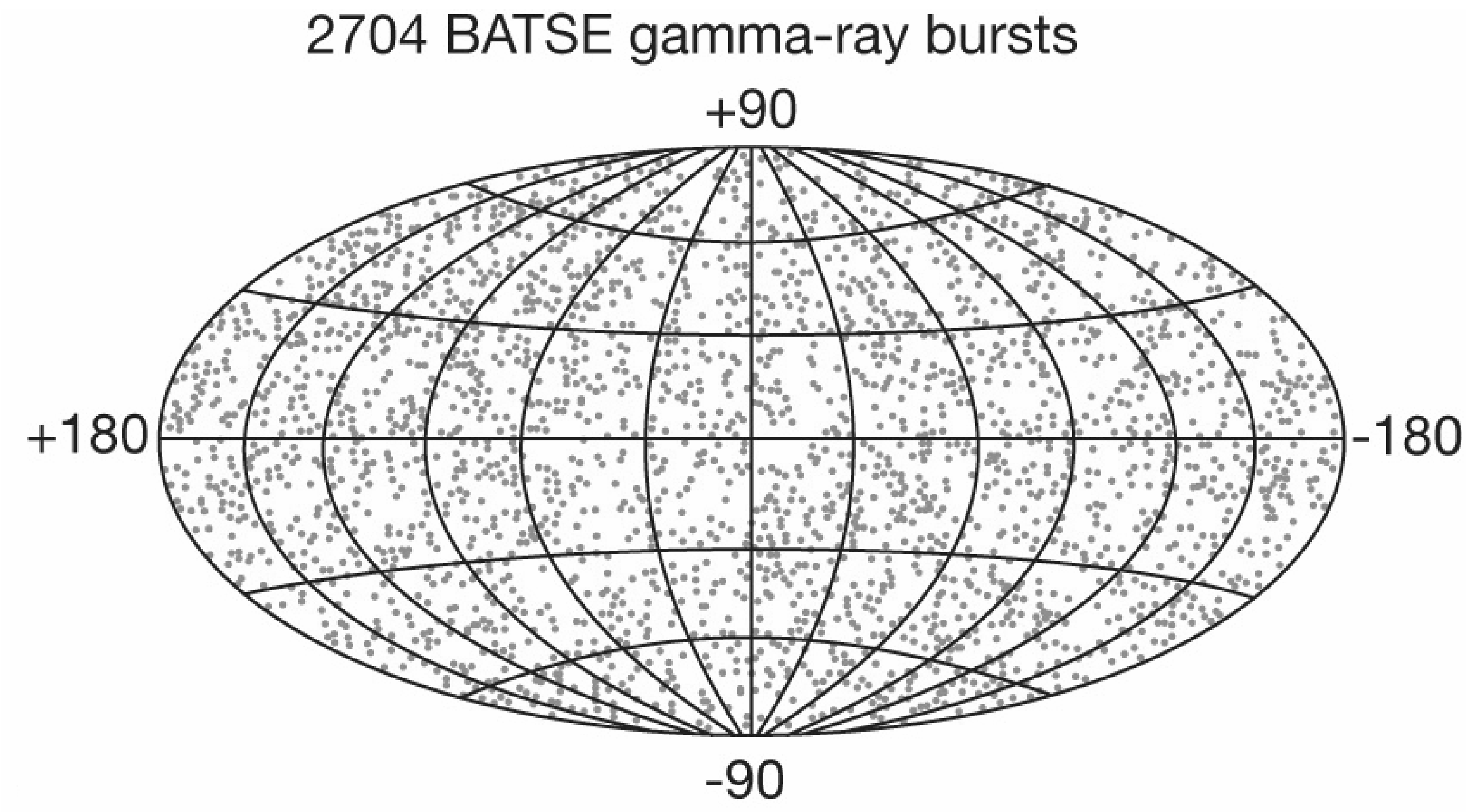
Millisecond pulsars are thought to be "spun-up" by matter falling in from a companion.



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

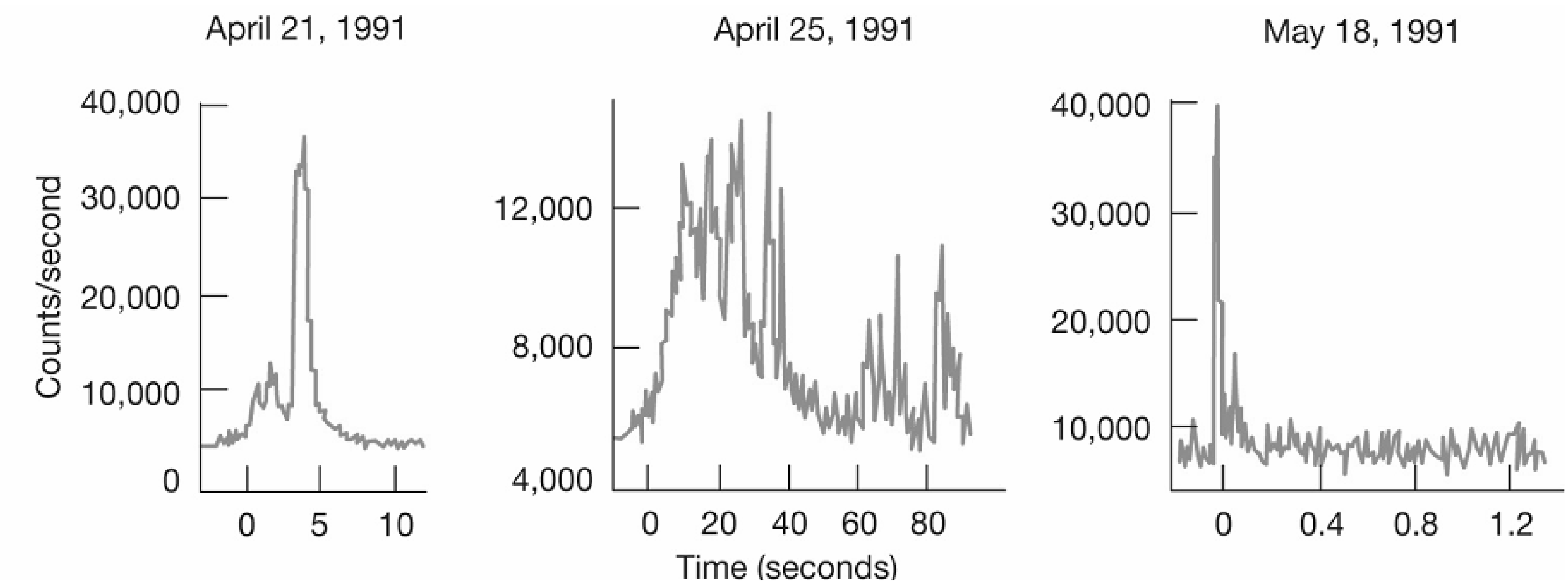
13.4 Gamma-Ray Bursts

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:



13.4 Gamma-Ray Bursts

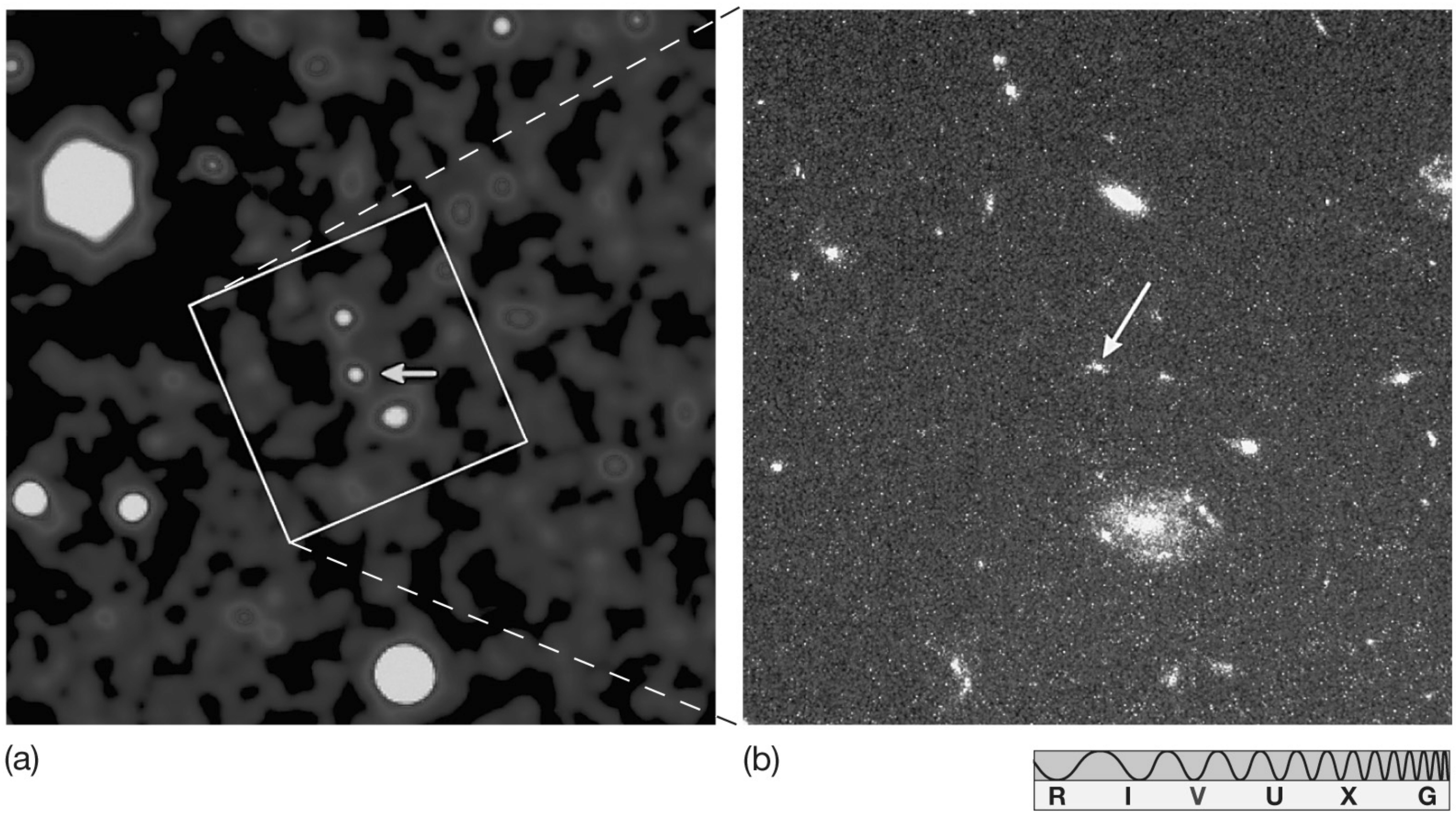
These are some sample luminosity curves for gamma-ray bursts:



13.4 Gamma-Ray Bursts

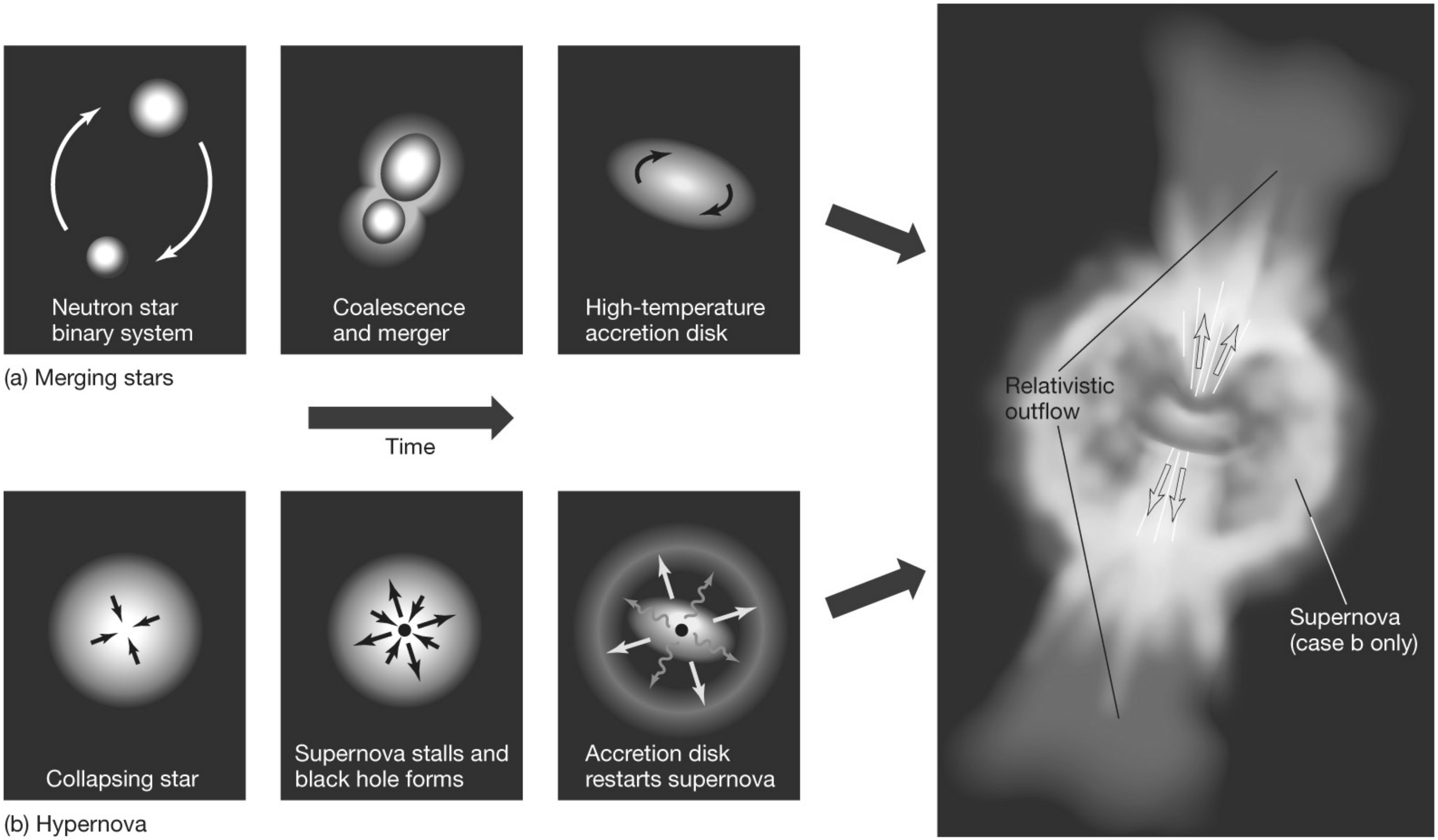
Distance measurements of some gamma bursts show them to be very far away – 2 billion parsecs for the first one measured.

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



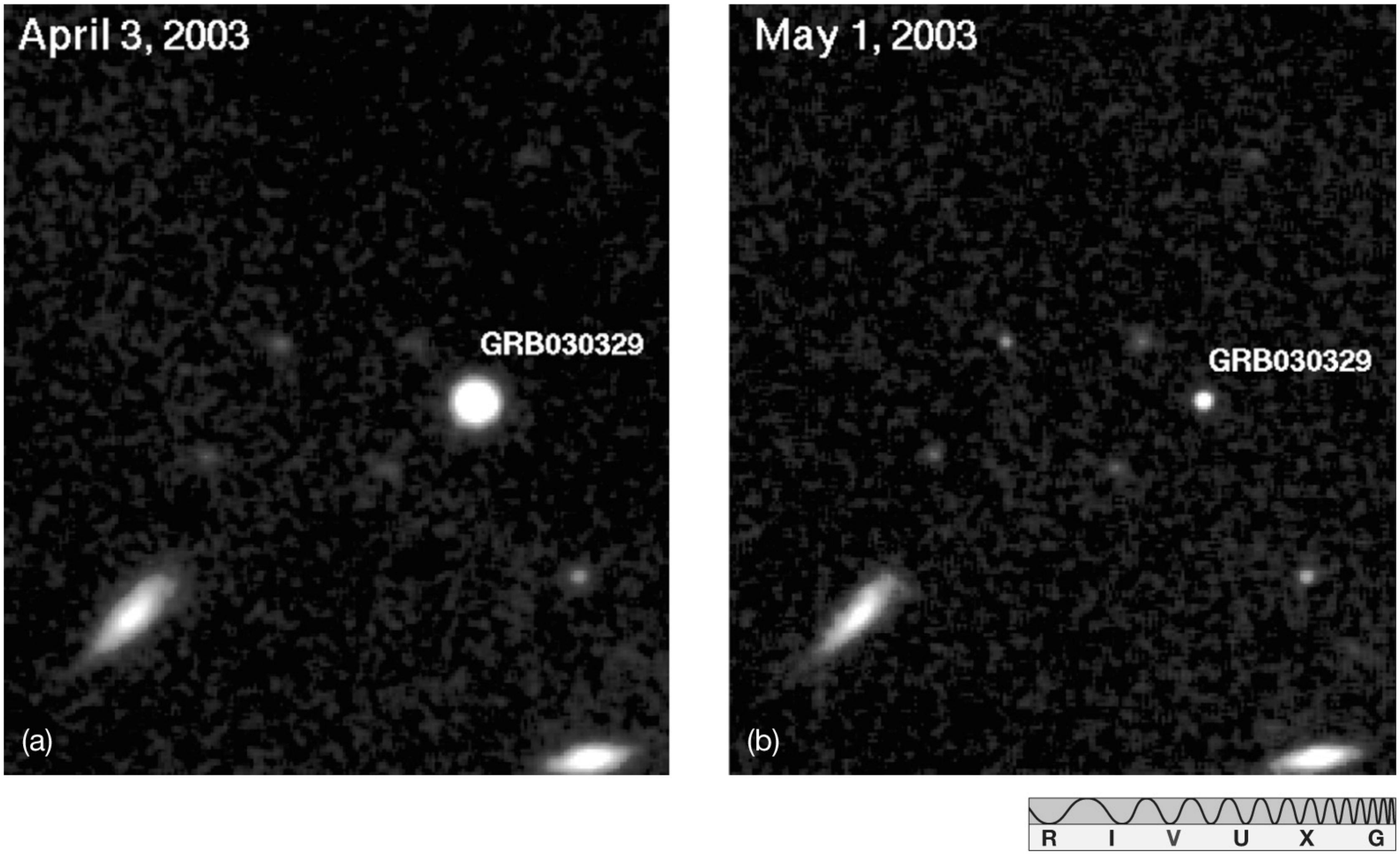
13.4 Gamma-Ray Bursts

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



13.4 Gamma-Ray Bursts

This burst looks very much like an exceptionally strong supernova, lending credence to the hypernova model:



13.5 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.

13.5 Black Holes

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

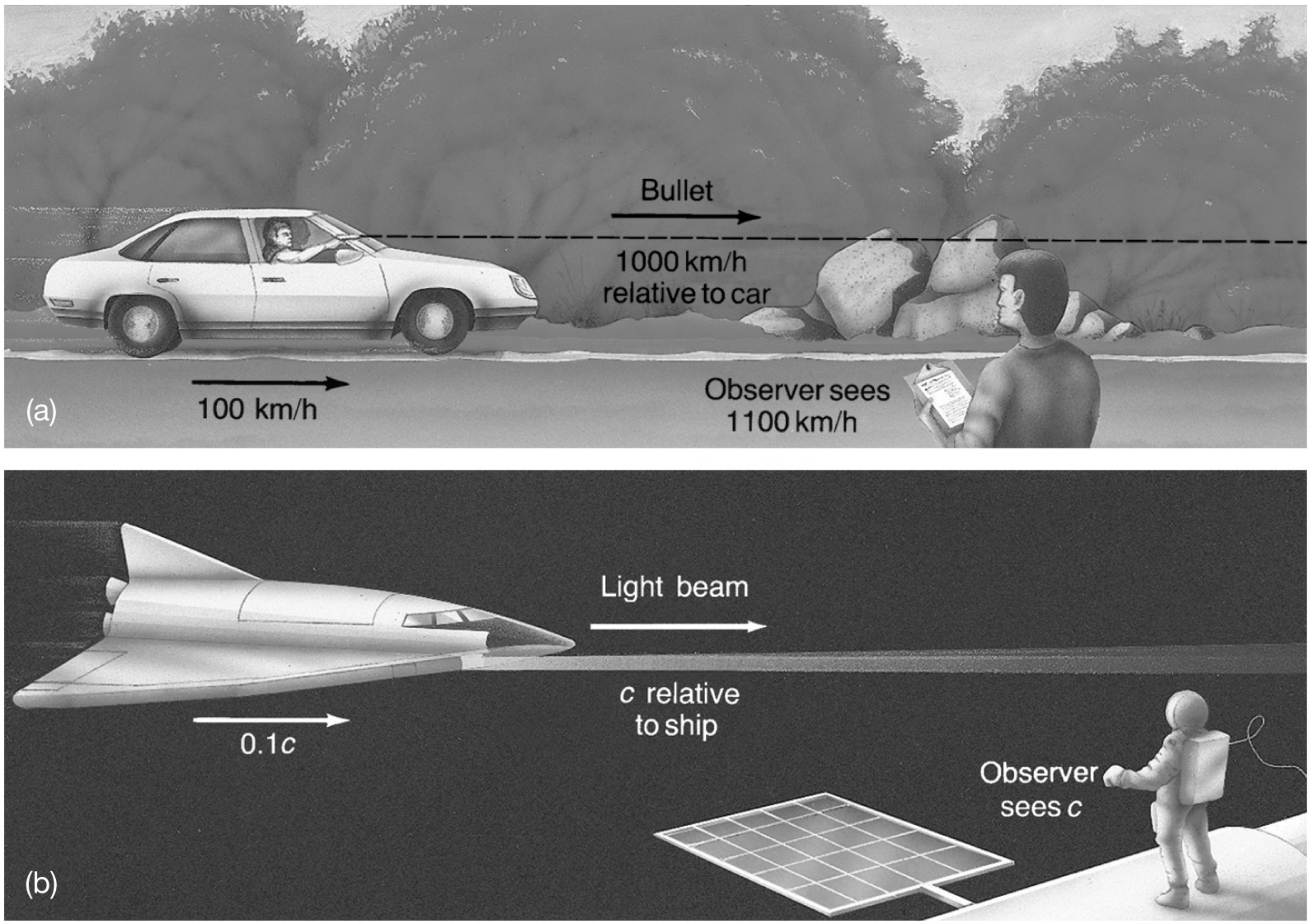
The Earth's Schwarzschild radius is about a centimeter; the Sun's is about 3 km.

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.

13.6 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:



13.6 Einstein’s Theories of Relativity

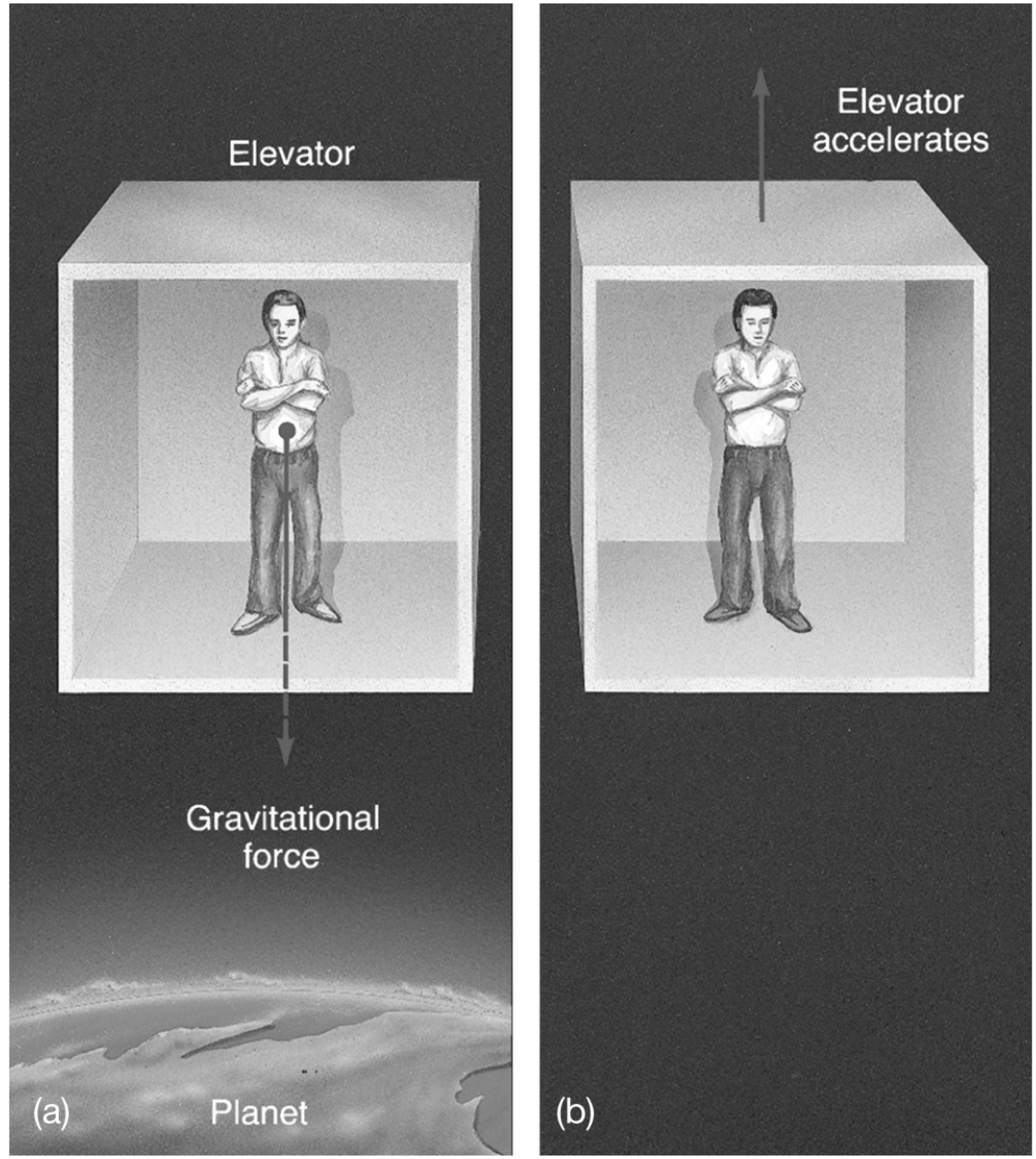
2. There is no absolute frame of reference, and no absolute state of rest.

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

13.6 Einstein's Theories of Relativity

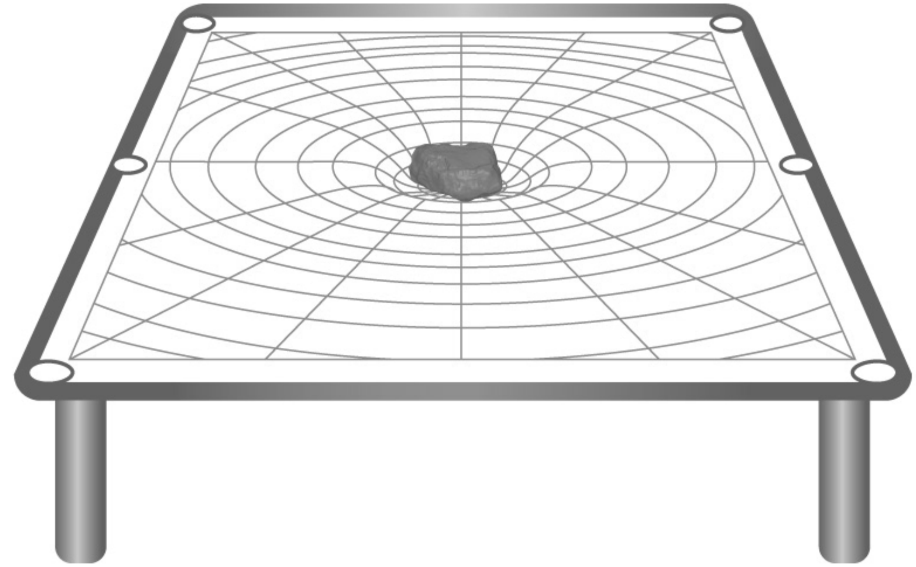
General relativity

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



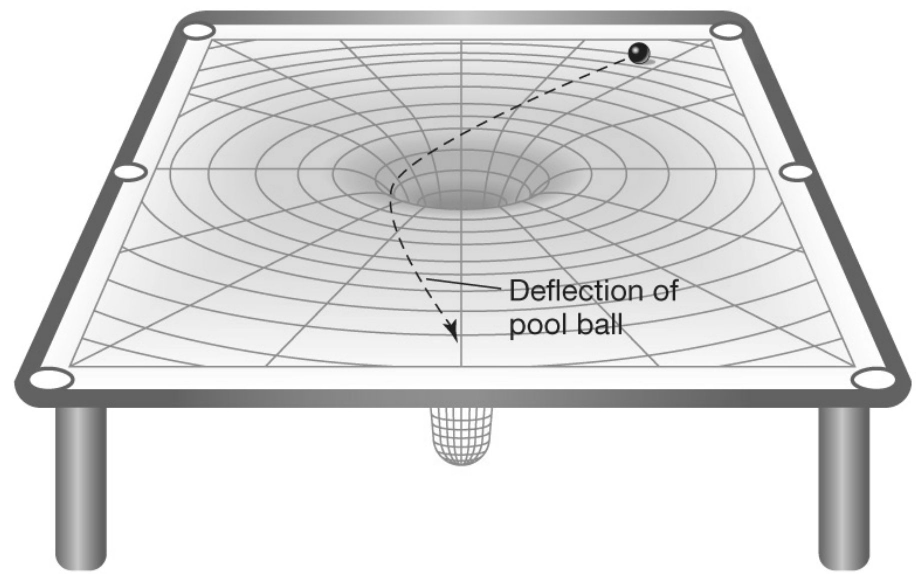
13.6 Einstein's Theories of Relativity

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



(a)

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



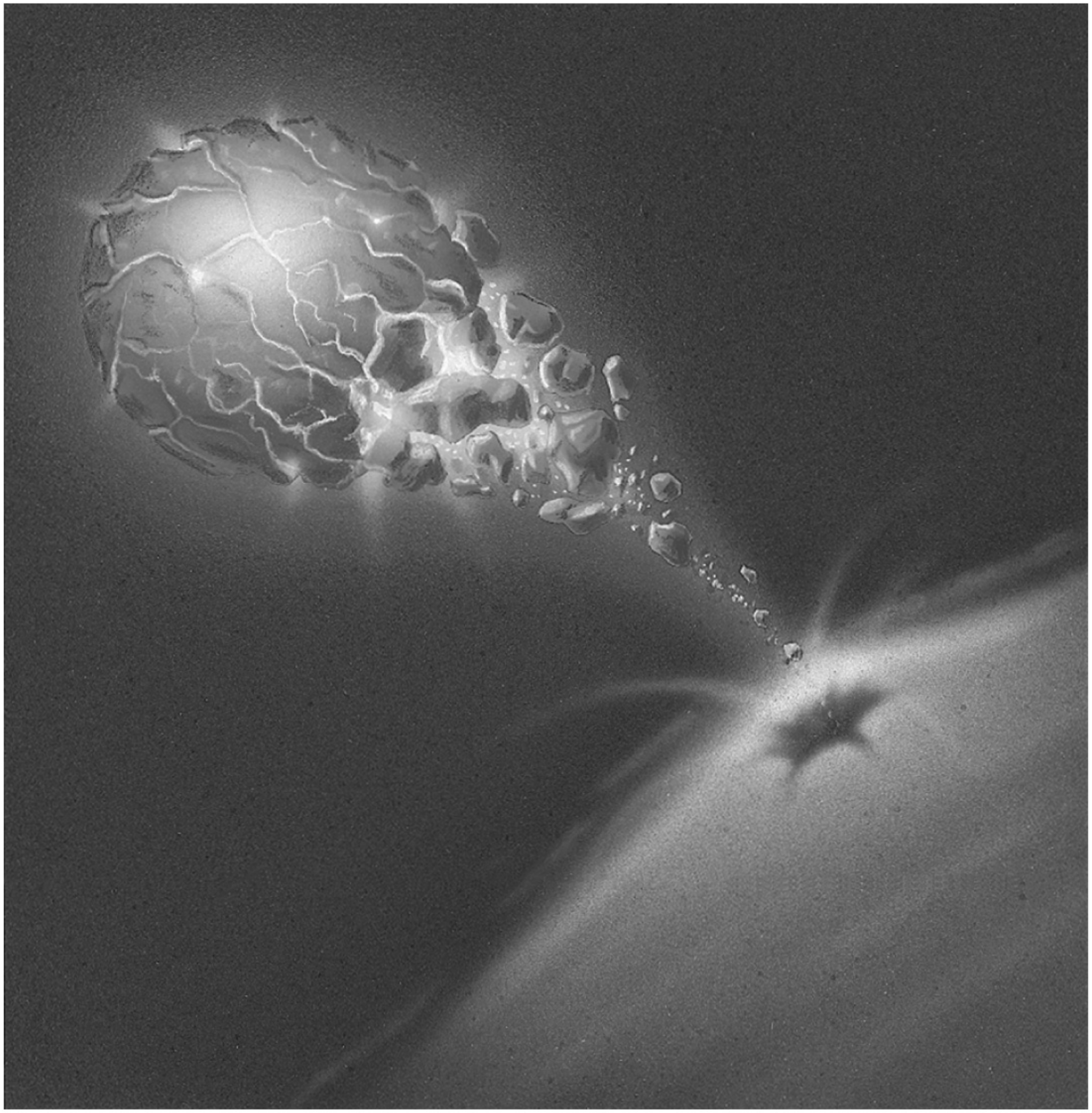
(b)

13.7 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.

13.7 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:



13.7 Space Travel Near Black Holes

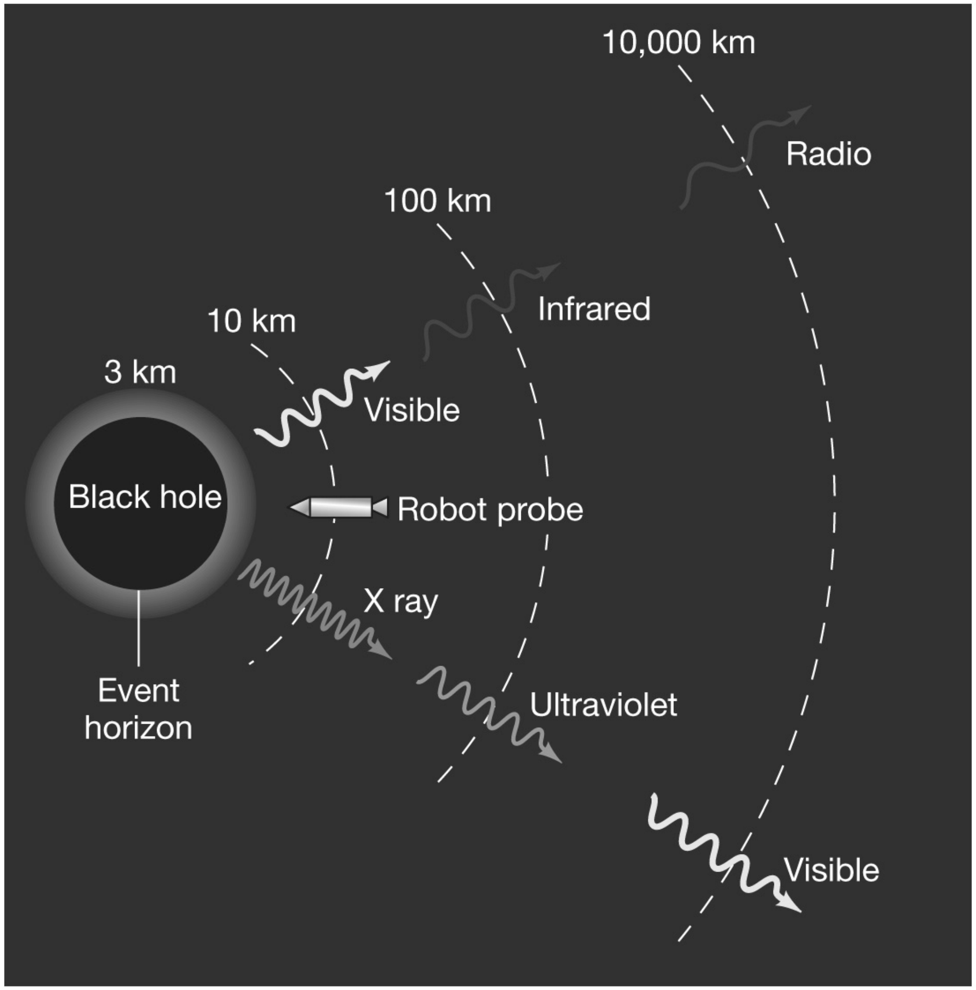
A probe nearing the event horizon of a black hole will be seen by observers as experiencing a dramatic redshift as it gets closer, so that time appears to be going more and more slowly as it approaches the event horizon.

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

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

13.7 Space Travel Near Black Holes

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



13.7 Space Travel Near Black Holes

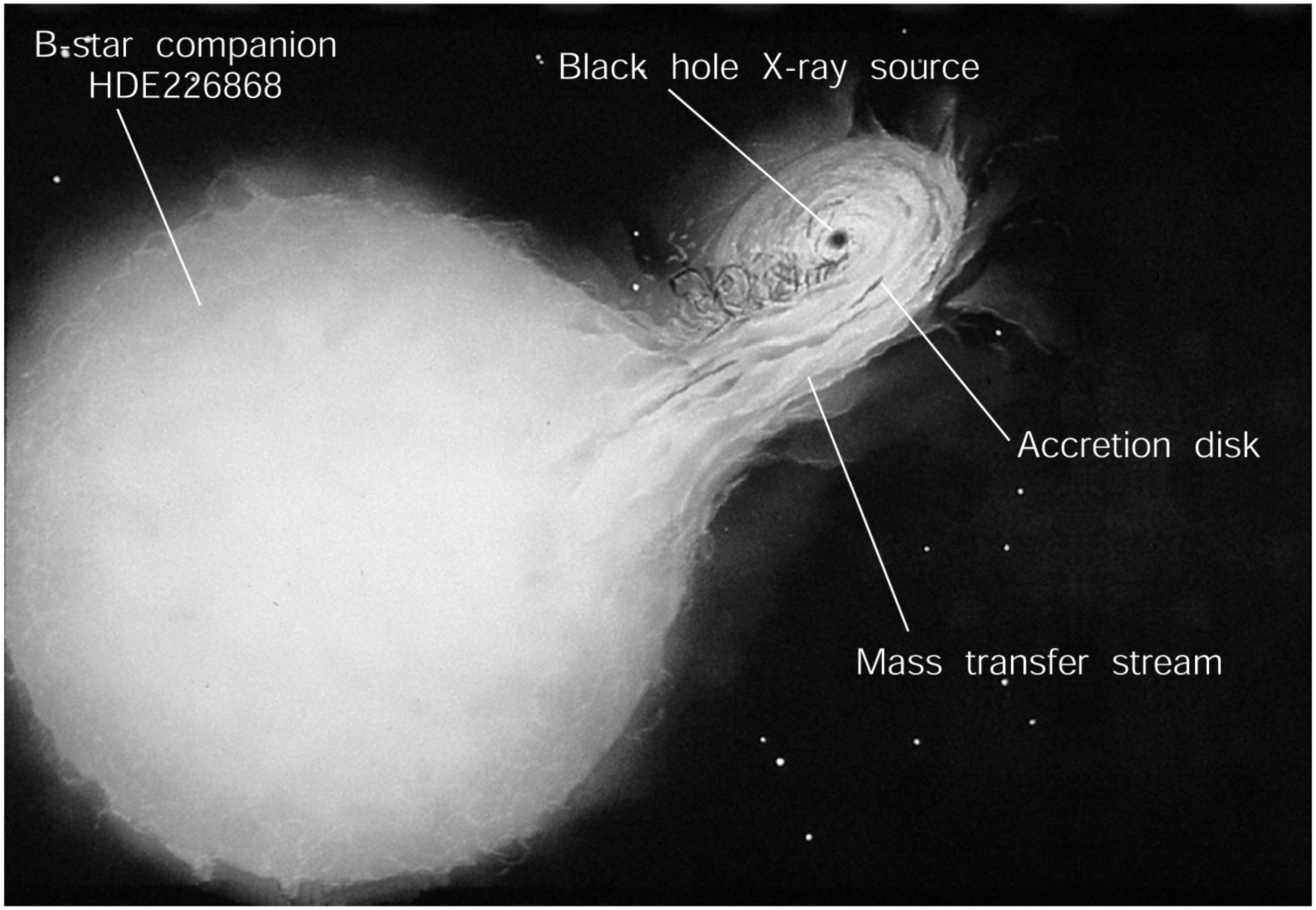
What's inside a black hole?

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

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

13.8 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.



13.8 Observational Evidence for Black Holes

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

• Its visible partner is about 25 solar masses

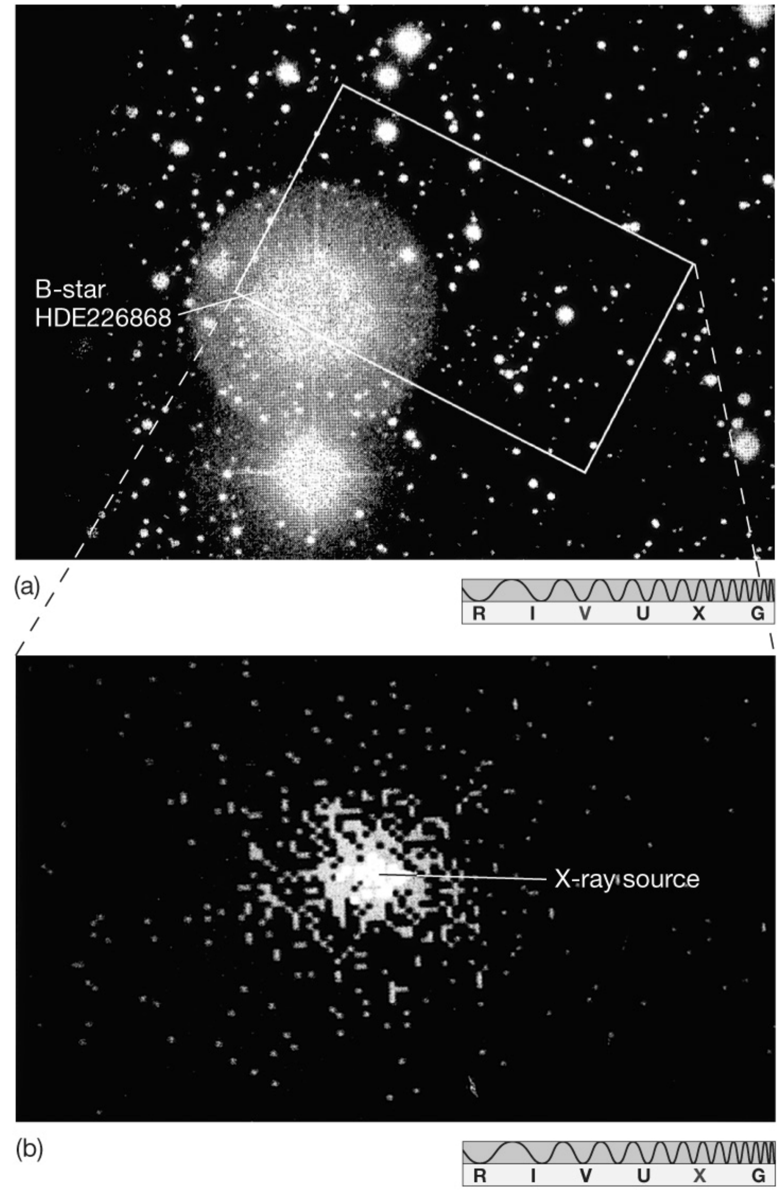
• The system's total mass is about 35 solar masses, so the X-ray source must be about 10 solar masses

• 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

13.8 Observational Evidence for Black Holes

Cygnus X-1, in visible light and X-rays:



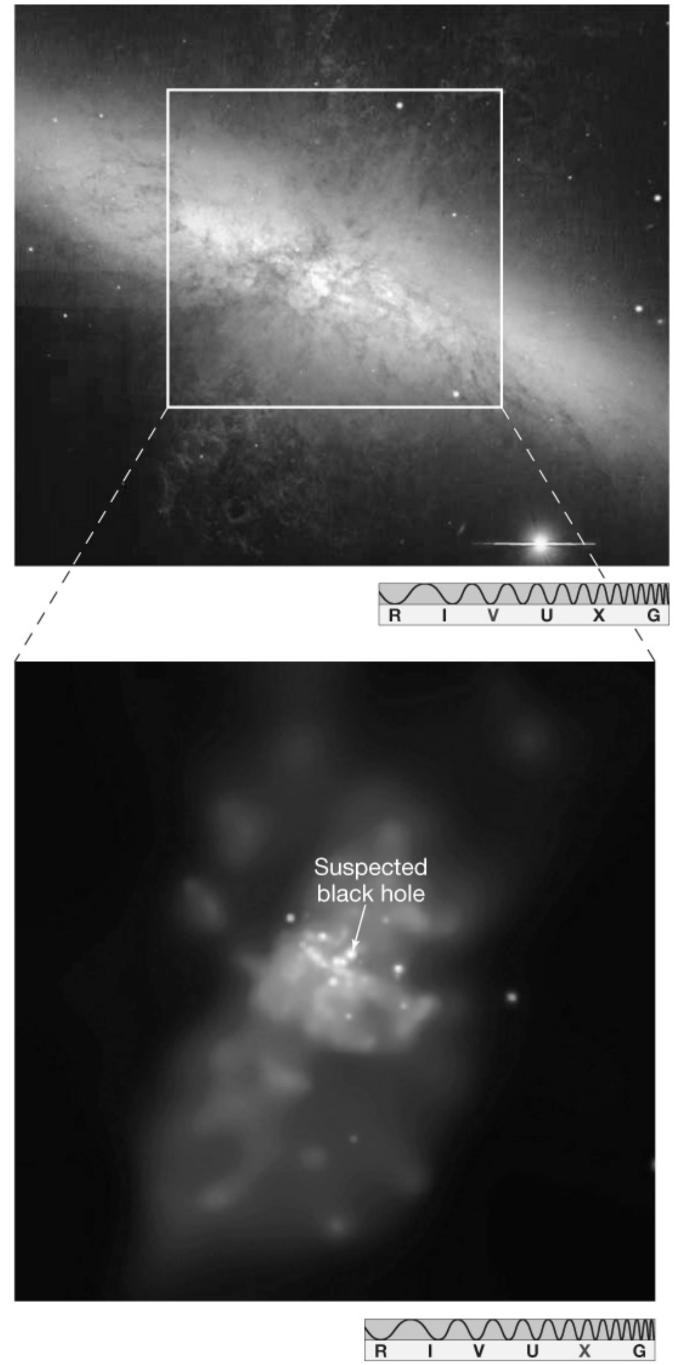
13.8 Observational Evidence for Black Holes

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

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

13.8 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.



Summary of Chapter 13

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

Summary of Chapter 13

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

Summary of Chapter 13

- **Distant observer would see 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**