Neutron Stars and Black Holes

Chapter 22

- Neutron Stars
- Pulsars
  - The Lighthouse Model
- Neutron Star Binaries
- Gamma-Ray Bursts
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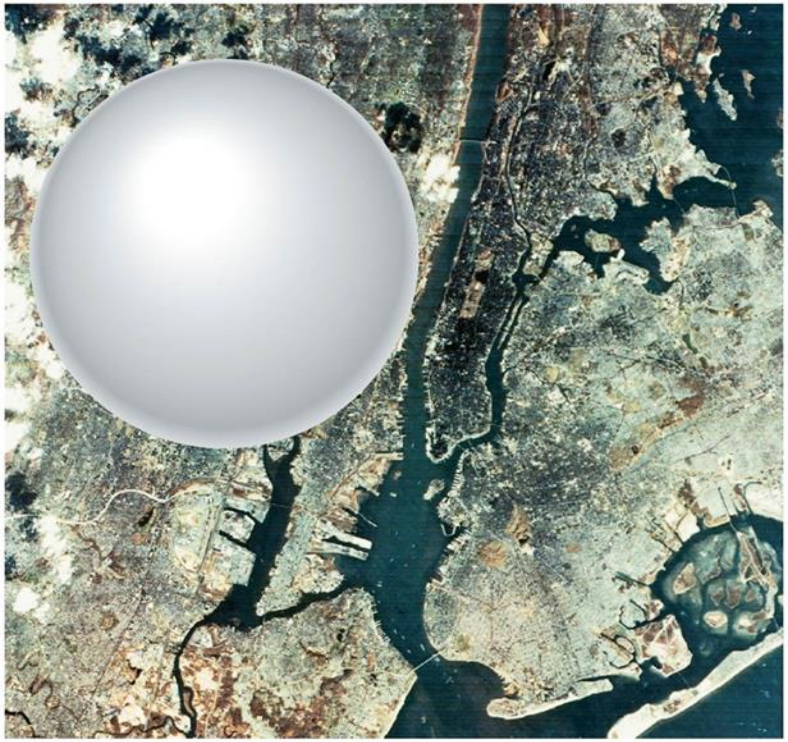
Neutron Stars

- After a Type I supernova, little or nothing remains of the original star.
- After a Type II supernova, part of the core may survive. The core is called a **neutron star** and will have a mass between 1 and 3 solar masses.

Neutron Stars: Five Facts

1. The neutron star is small: its radius is about 10 km (diameter 20 km, about the length of Manhattan island).
2. It is very dense—as dense as an atomic nucleus. The density is about 10^{17} - 10^{18} $\mathrm{kg/m^3}$. One ***teaspoon*** of a neutron star would have a mass of ***one billion tons***.



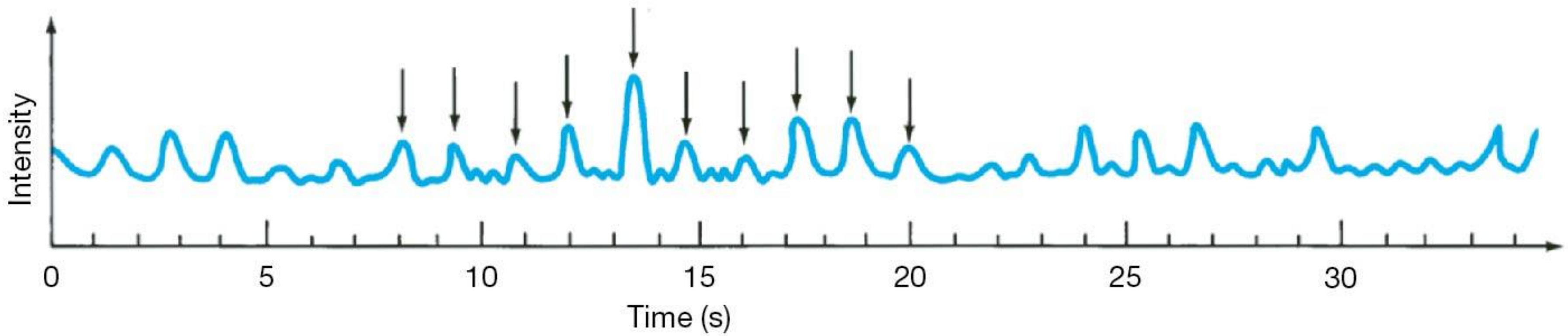
(Mt. Everest has a total mass of about 150 billion tons.)

Neutron Stars: Five Facts

3. The surface gravity of the neutron star is huge! The acceleration due to gravity on the surface would be roughly 2.5×10^{12} m/s^2, so a 70 kg person would have the same weight as 10-20 billion tons on earth! A water bottle full of neutron star material would weigh more than Mt. Everest does on Earth.
4. Neutron stars rotate rapidly, several times a second. (This is required by conservation of angular momentum.) The rotation rate slows in time.
5. New-born neutron stars have strong magnetic fields, typically 1 trillion times that of Earth.

Pulsars

- **Pulsars** are small objects that emit powerful bursts radiation in the form of rapid pulses.
- The first pulsar was discovered in 1967 by a graduate student at Cambridge named Jocelyn Bell.
- It emitted extraordinarily regular pulses.



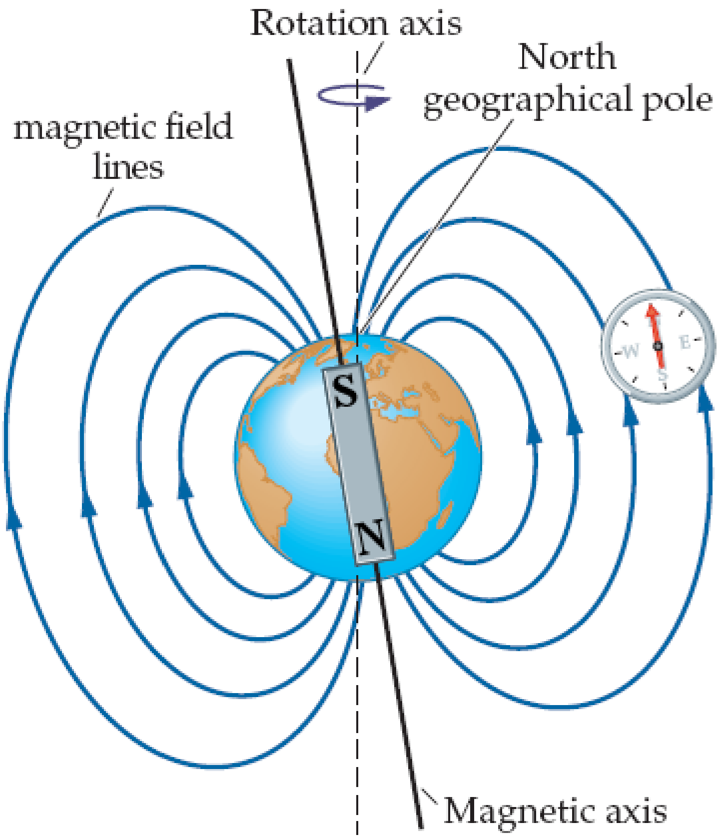
- Her thesis advisor, Antony Hewish, proposed that pulsars were neutron stars, spinning very rapidly.

Pulsars

- **Hewish's reasoning**:
- Only rotation could produce pulses with the kind of regularity characteristic of pulsars.
- Pulses could be produced if the geographic north pole and the magnetic north pole do not coincide. This is called the **Lighthouse Model**.
- The source could not be more than a few tens of kilometers across, otherwise radiation from different portions of the source would blur the pulses because they would arrive at slightly different times.
- More than 1500 of these have been discovered in the Milky Way, so far.

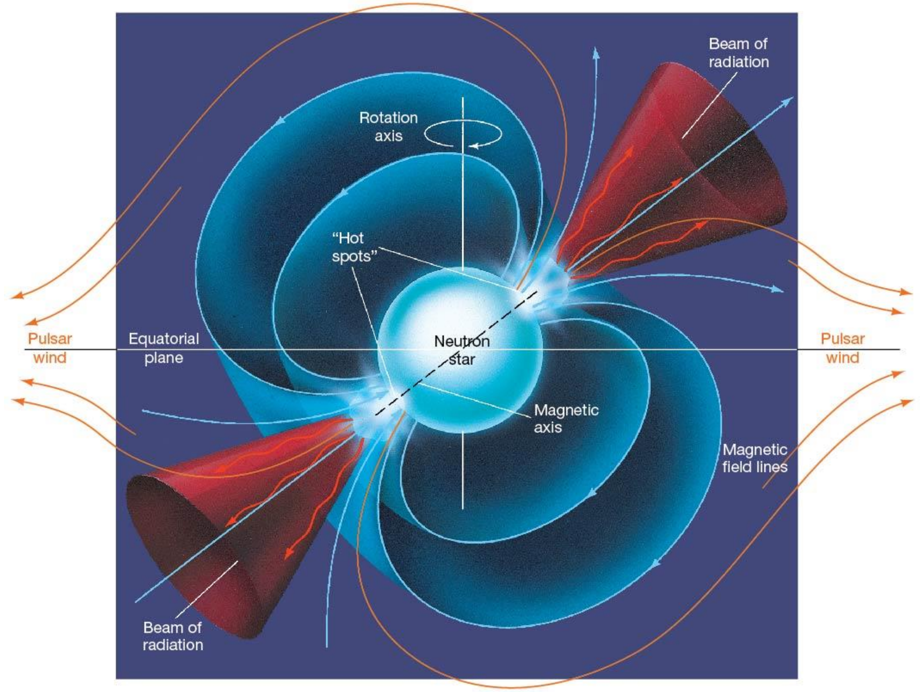
Pulsars

- The geographic poles lie along the axis of rotation.
- No physics requires the magnetic and geographic poles to coincide. The do not coincide for Earth.



Lighthouse Model

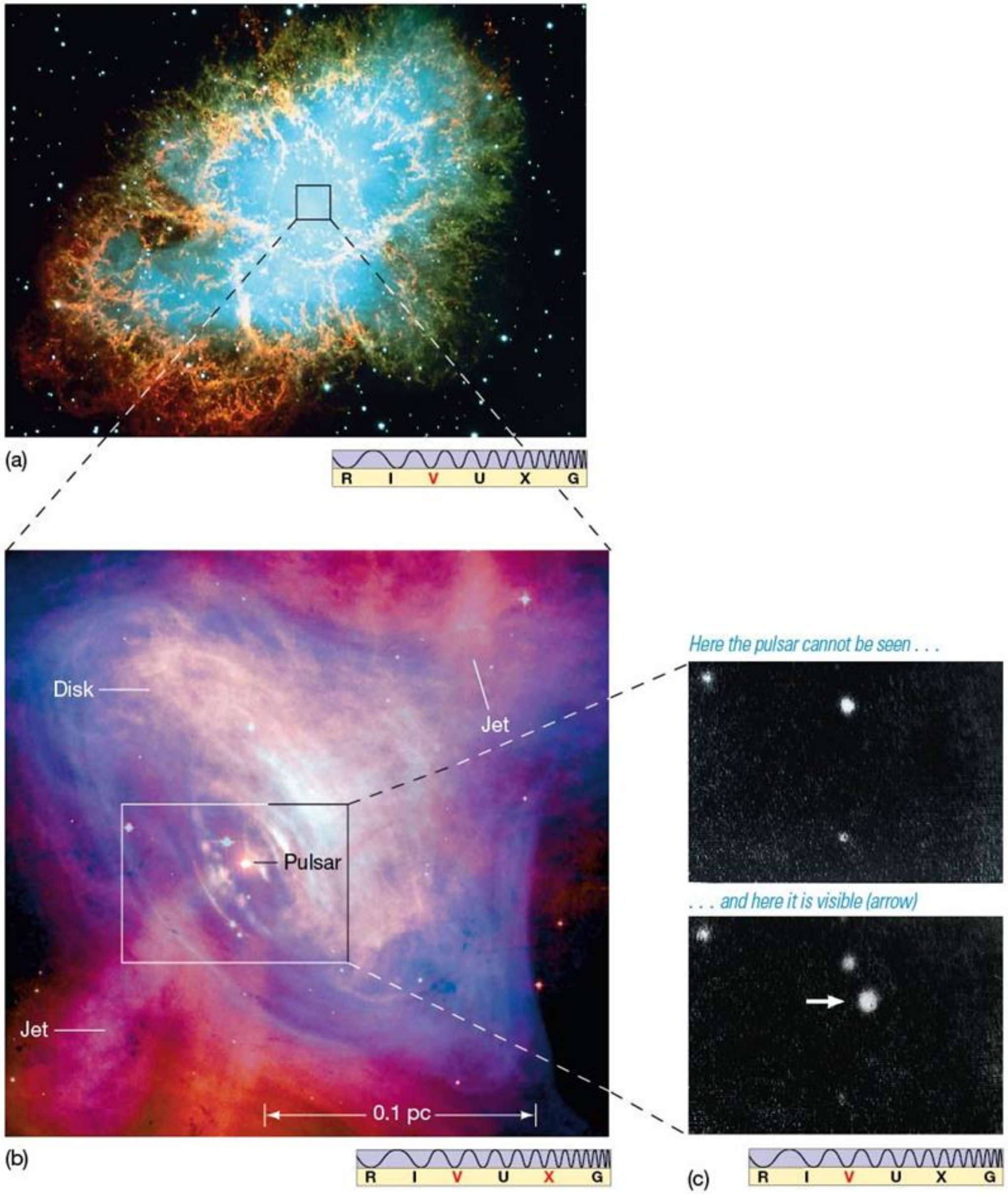
- **Why would a neutron star flash on and off?** This figure illustrates the lighthouse effect responsible.
- Strong jets of matter are emitted at the magnetic poles, as that is where they can escape. If the rotation axis is not the same as the magnetic axis, the two beams will sweep out circular paths.
- If Earth lies in one of those paths, we will see the star blinking on and off.



A lighthouse beacon is a good analogy for a rotating pulsar.

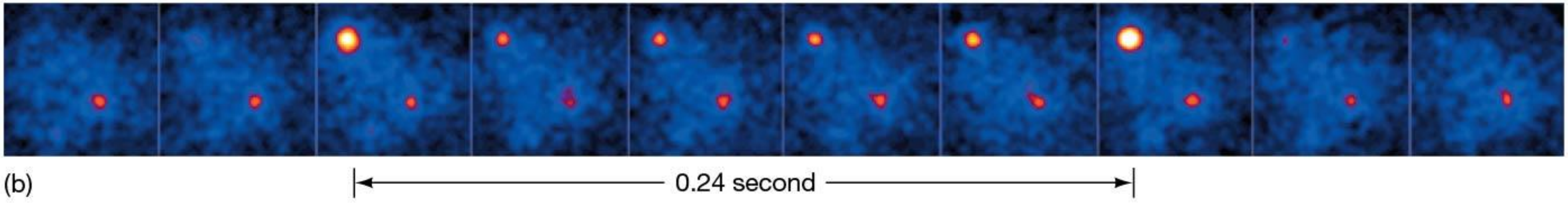
Pulsars

- 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.
- The Crab nebula pulsar is on the right.



Pulsars

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



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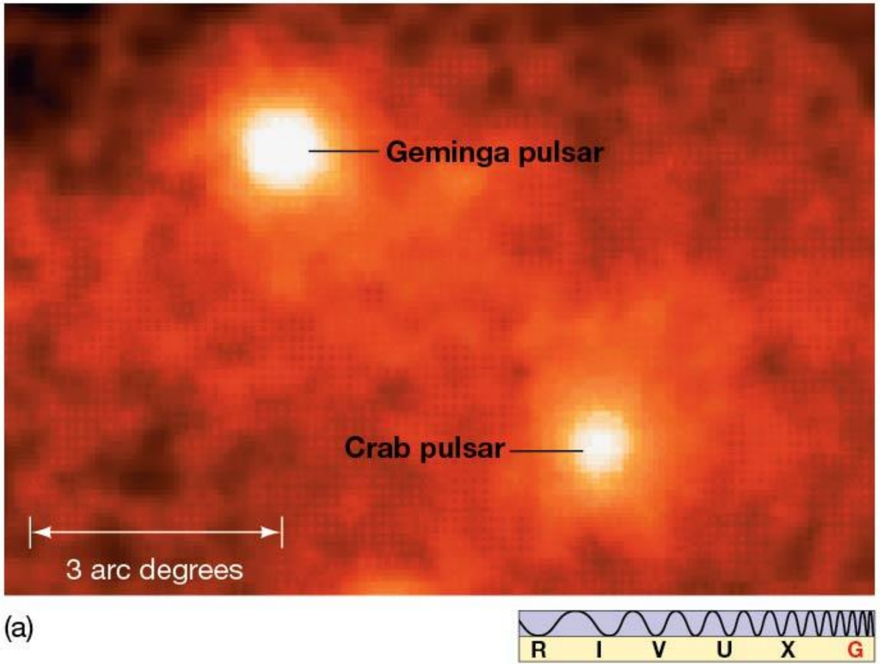
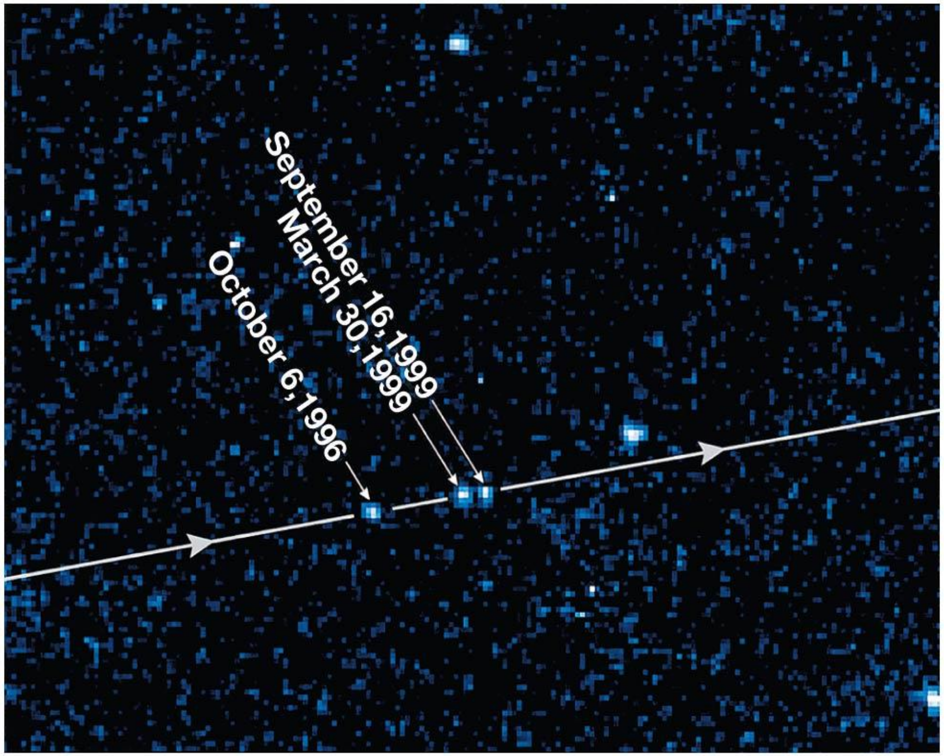
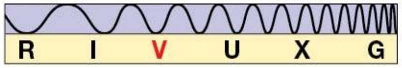


(a)

Pulsars

- Most pulsars have been observed with very high velocities. This is because of asymmetries in the supernova from which it formed (neutrino jets). About 50% of them have $v > 800$ km/s.
- On the right, an isolated neutron star, observed by the *Hubble* telescope, is moving rapidly. It has a surface temperature of 700,000 K, and is about 1 million years old.



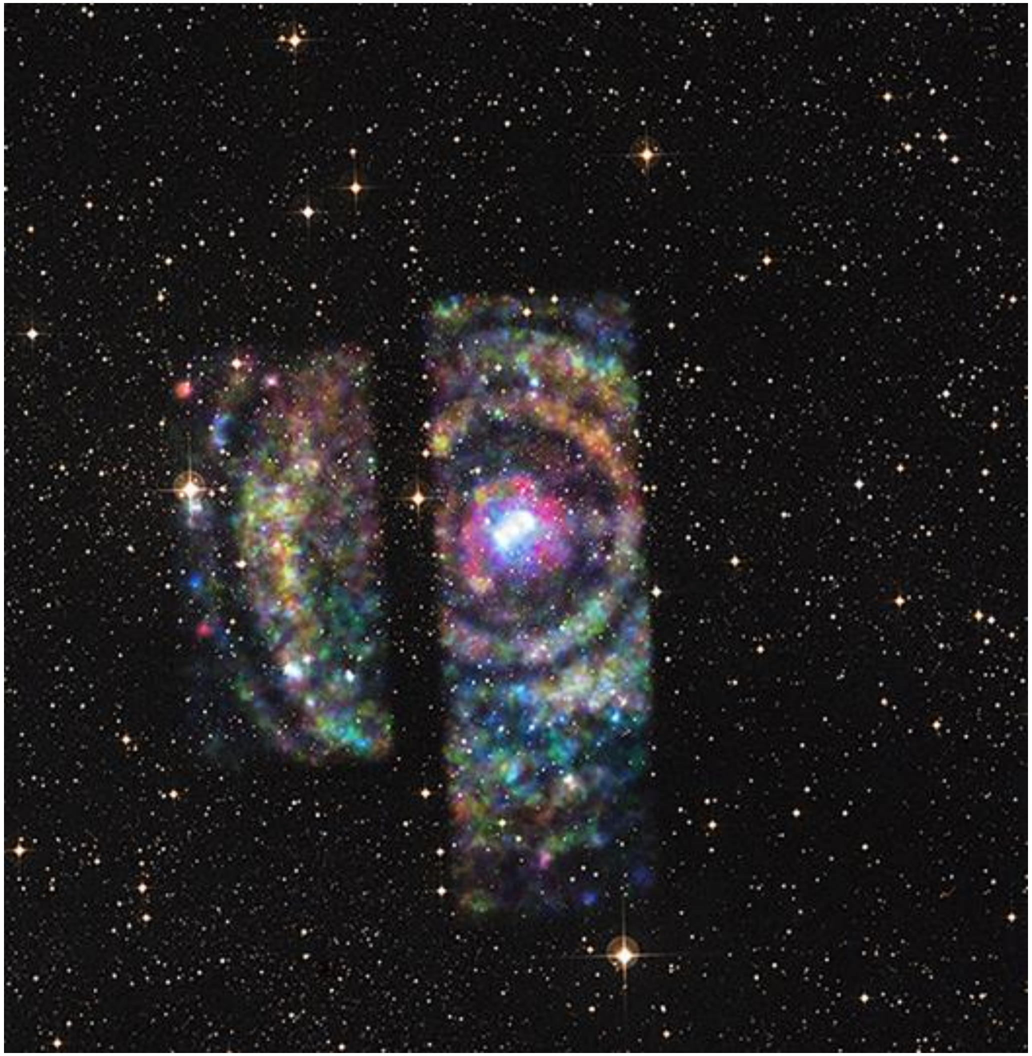


Pulsars

- While all pulsars are neutron stars, not all neutron stars are pulsars:
  - We see a pulsar only if the light beams happen to be directed our way.
  - Within a few tens of millions of years, the magnetic field loses energy, the beams weaken and the pulses stop.
  - One can estimate that for every pulsar we observe there must be 100,000 more neutron stars moving about unseen.
- White dwarfs, Neutron stars and Black Holes were predicted by theory decades before they were actually observed.

Neutron Star Binaries

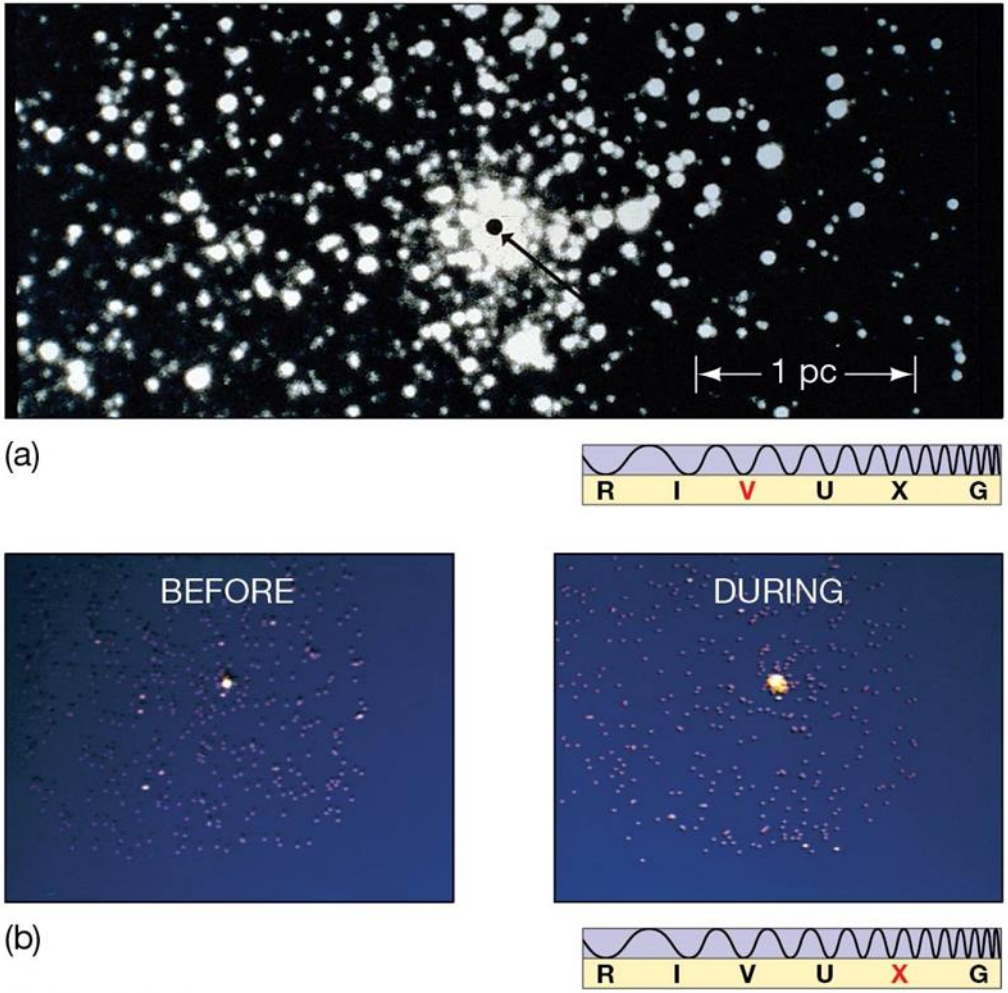
- Most neutron stars are expected to have formed in binary systems.
- At least some neutron stars do have binary companions.
- This has allowed us to measure their masses with good accuracy.
- Most observed neutron stars masses are about 1.4 – 2.5 solar masses.



Circinus X-1 is a NS- binary

Neutron Star Binaries: X-Ray Bursts

- Bursts of X-rays have been observed near the center of our galaxy. A typical one is shown on the right

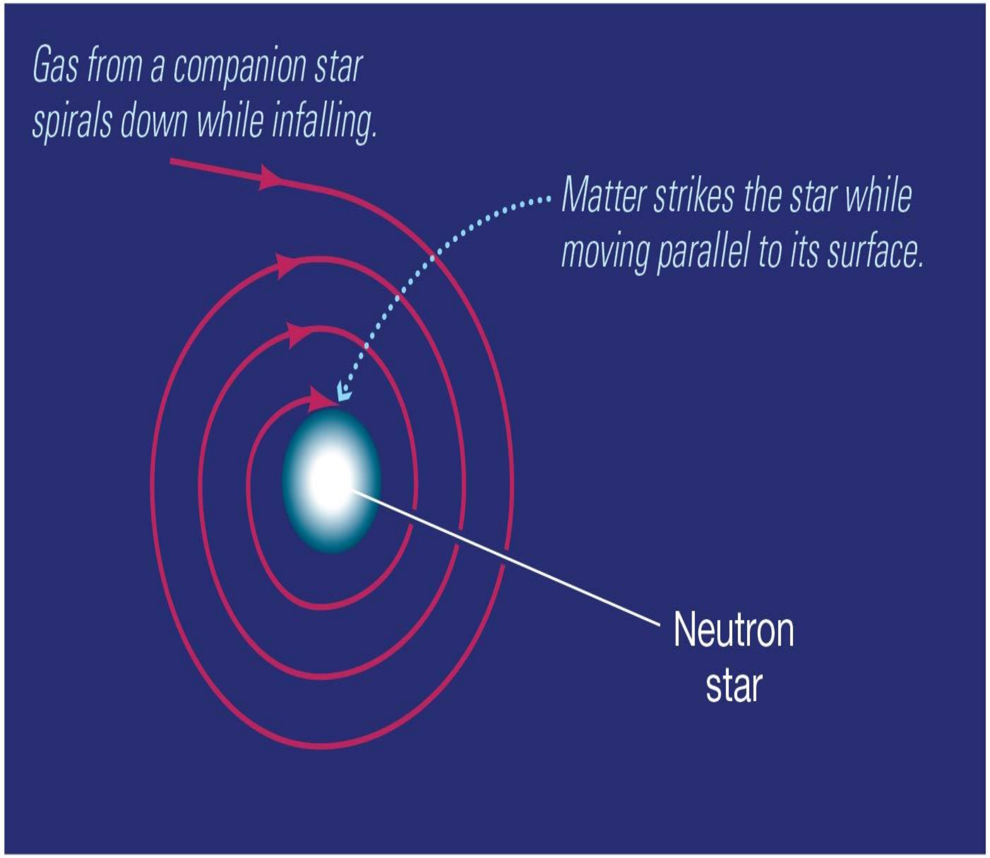


Neutron Star Binaries: X-Ray Bursts

- 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.

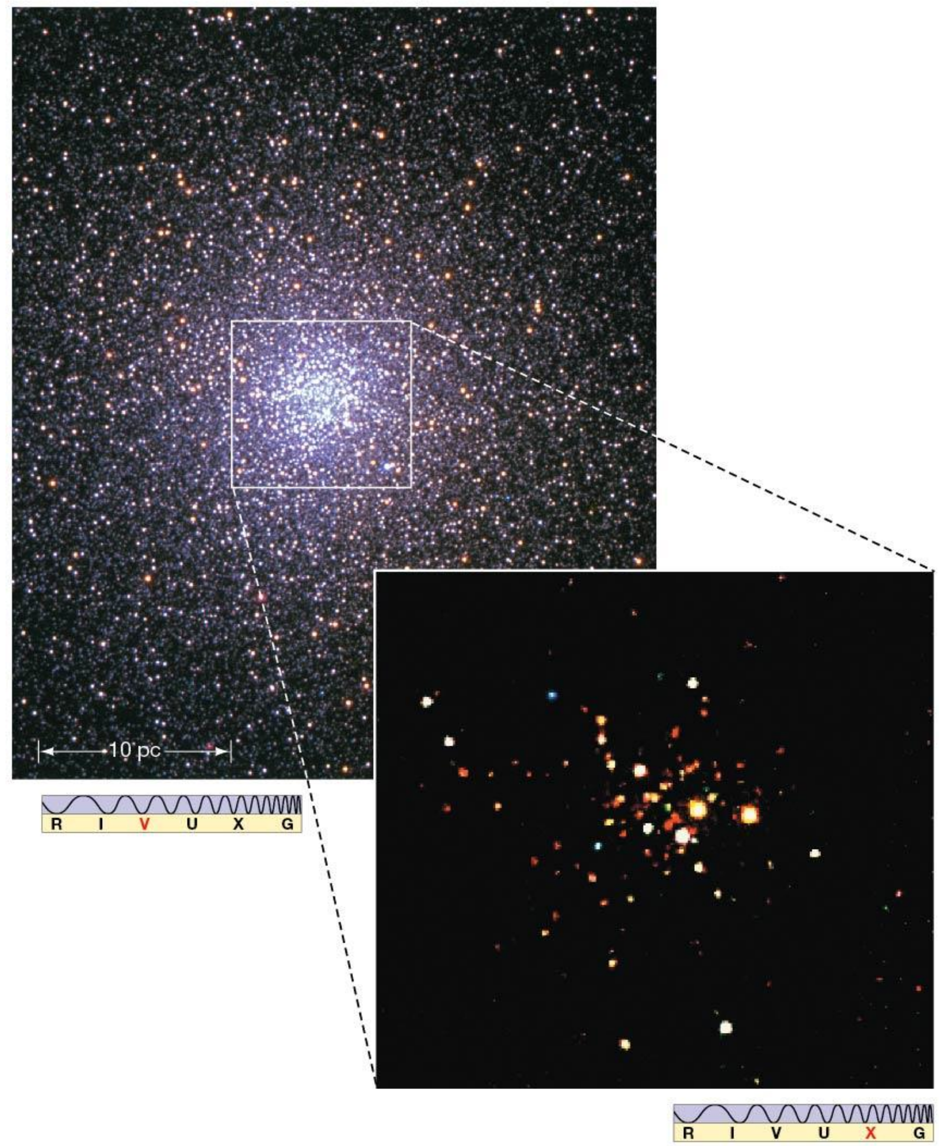
Neutron Star Binaries: Millisecond Pulsars

- 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 rotate hundreds of times per second.
- Millisecond pulsars are thought to be "spun-up" by matter falling in from a companion.



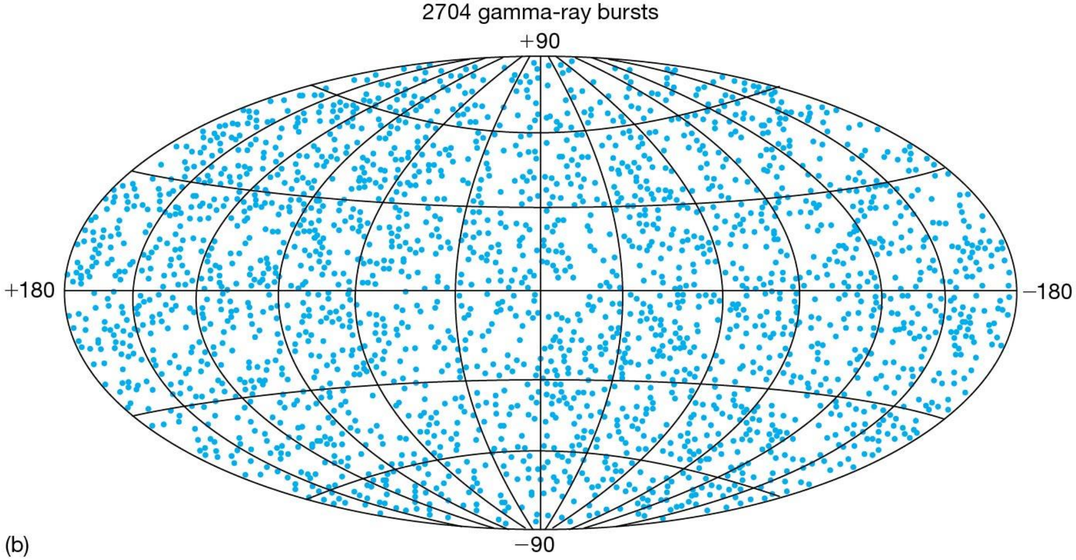
Millisecond Pulsars: X-ray Bursts

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



Neutron Star Binaries: 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**.



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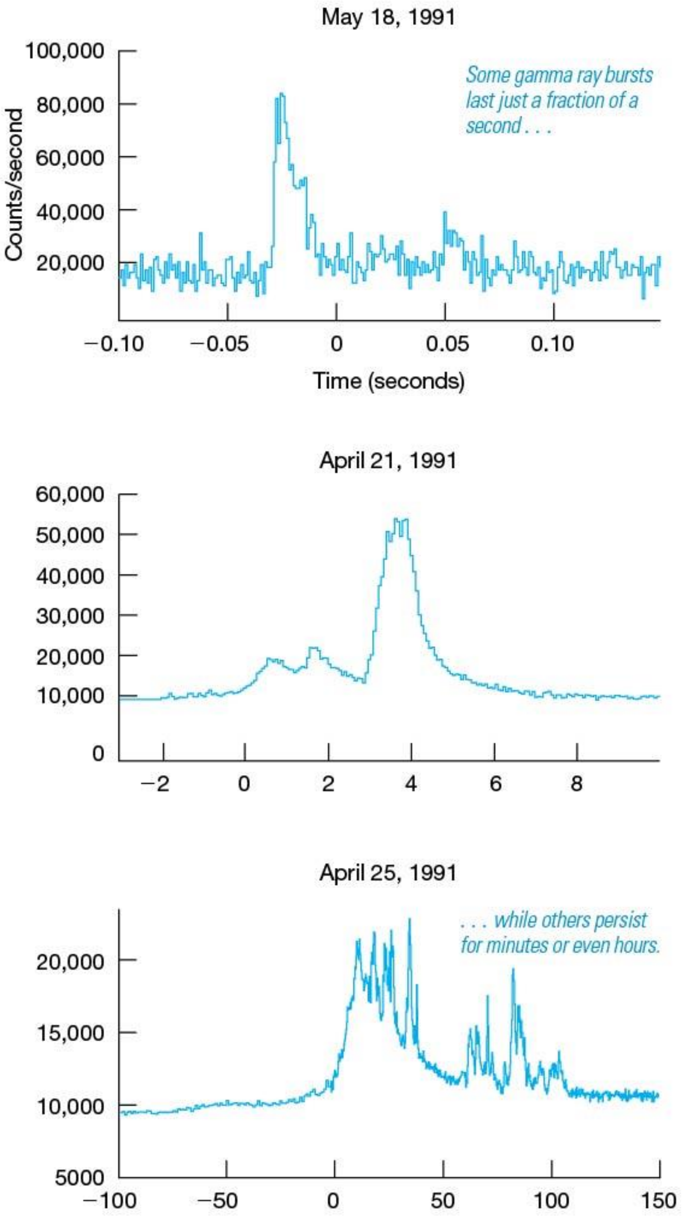
Neutron Star Binaries: Gamma Ray Bursts

- These are some sample curves plotting gamma-ray intensity versus time for gamma-ray bursts.



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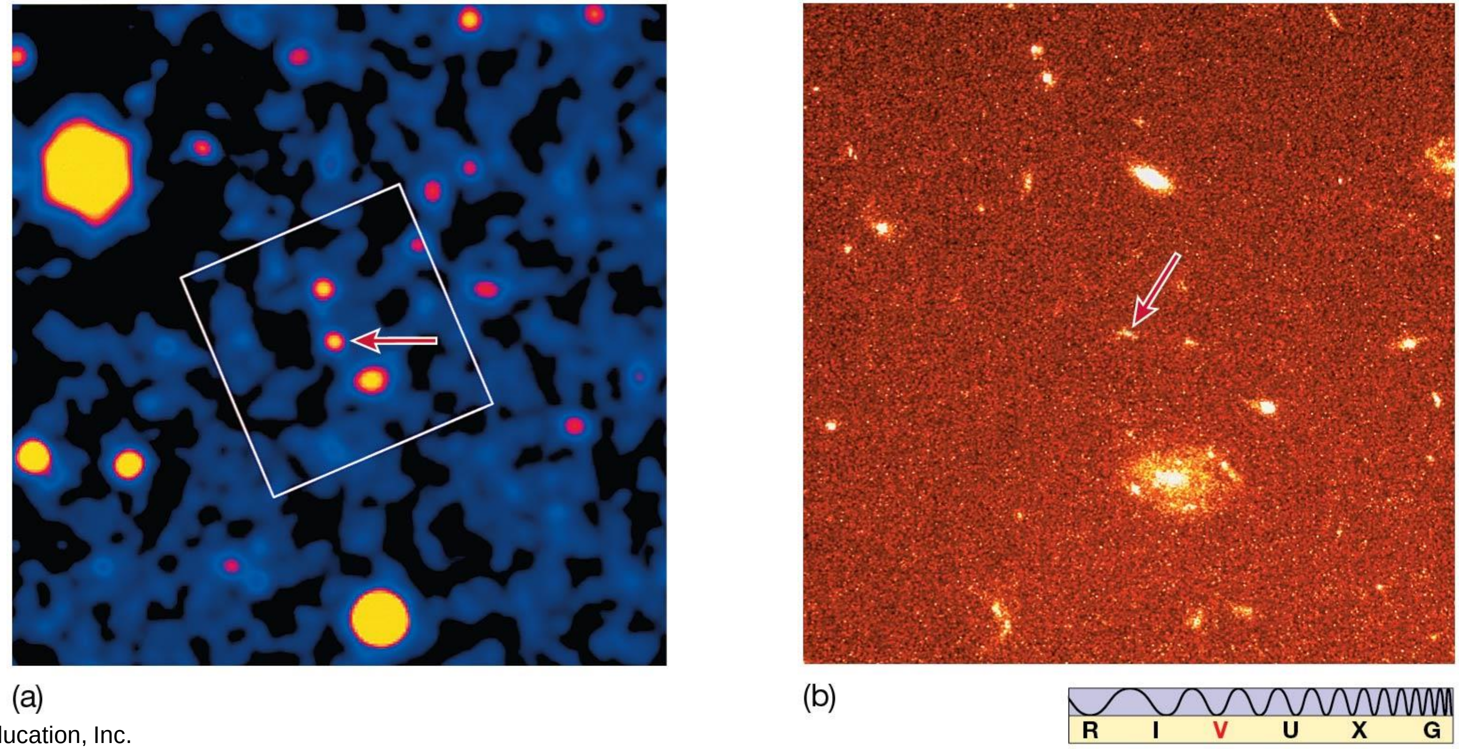
Neutron Star Binaries: Gamma Ray Bursts

- Occasionally, the spectrum of a burst can be measured, allowing distance determination
- Distance measurements show them to be very far away—2 billion parsecs for the first one measured.

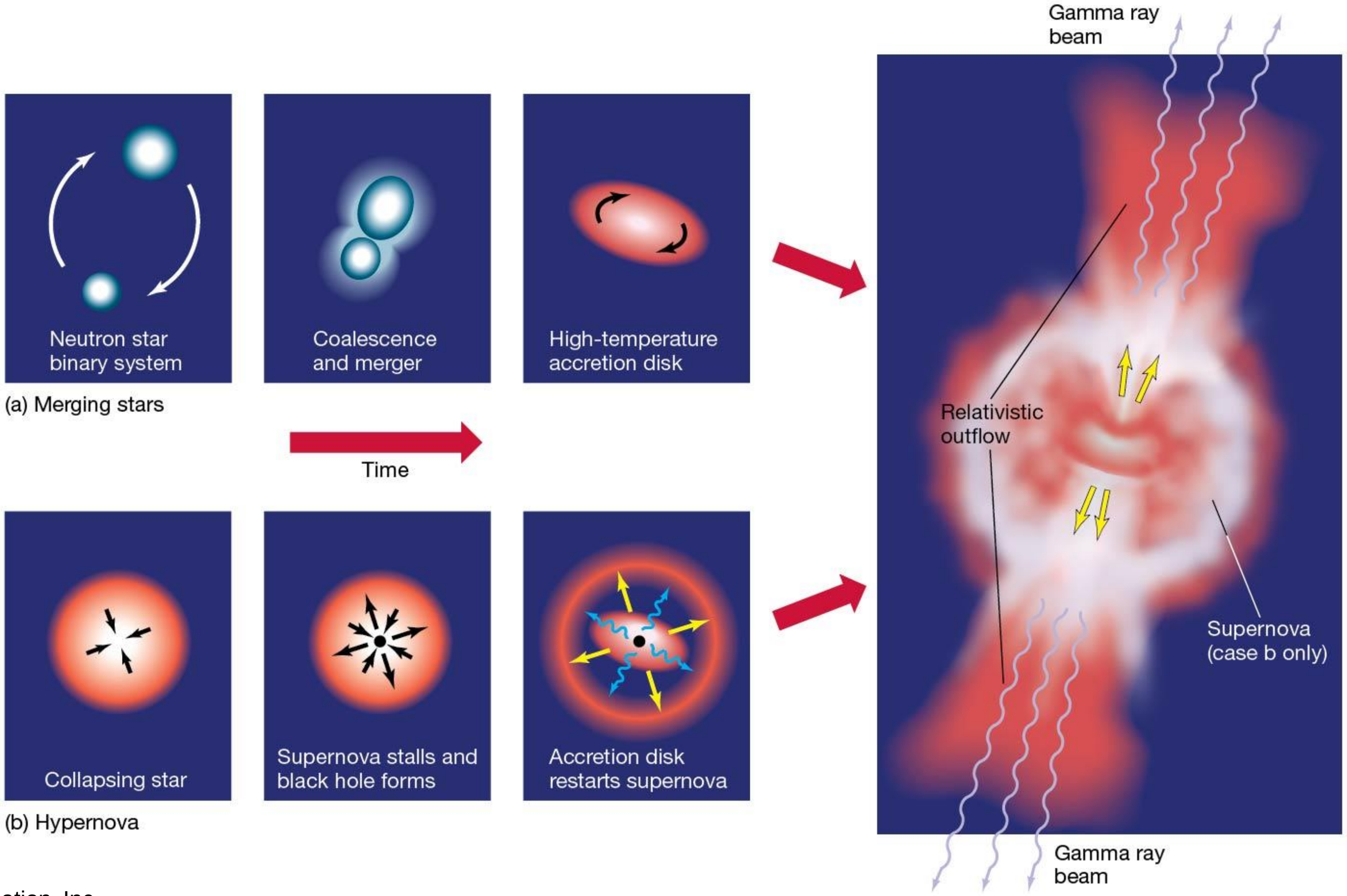


Black Holes

- The mass of a neutron star cannot exceed about 3.5 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**.

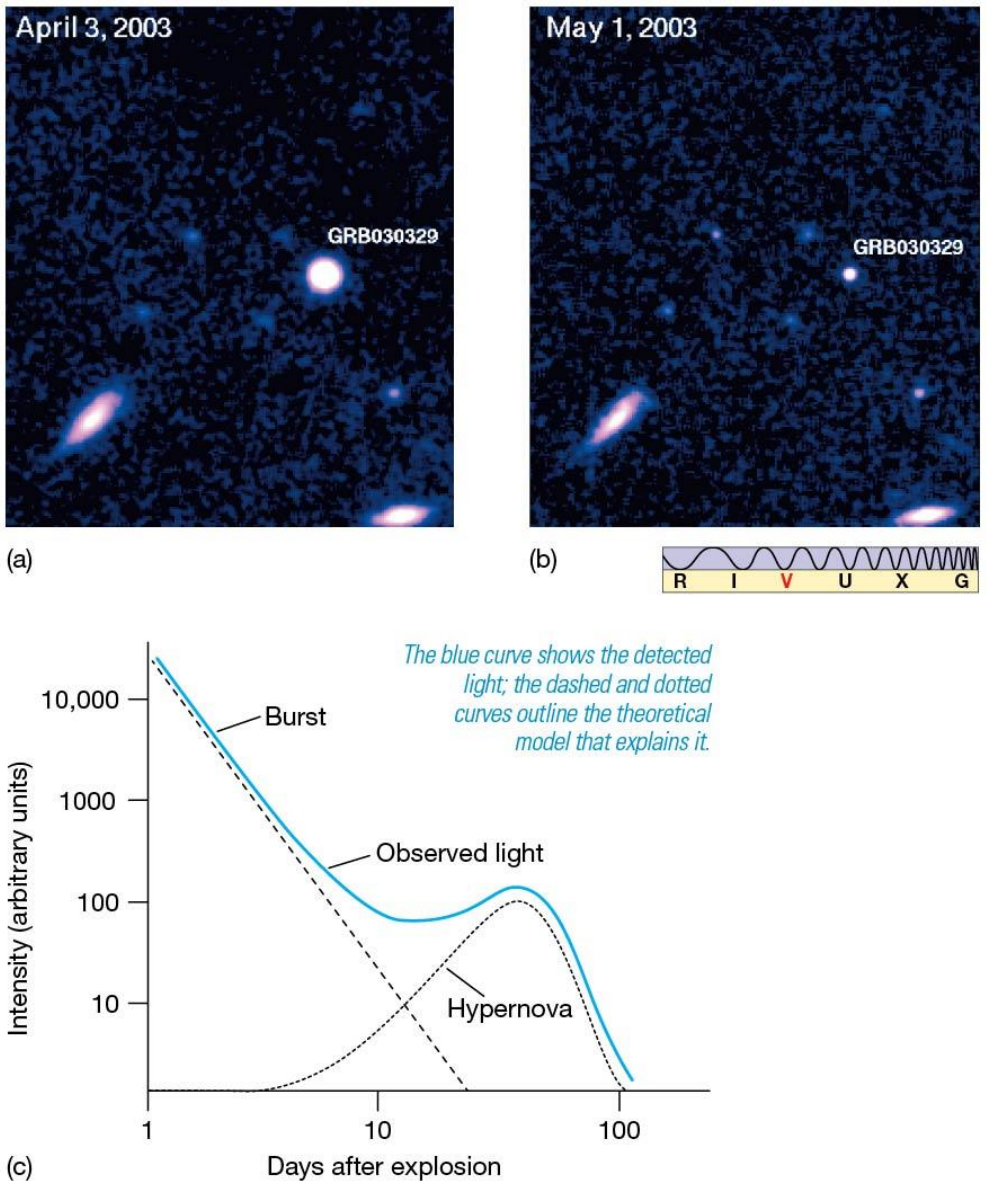
Neutron Star Binaries: Gamma Ray Bursts

- Two models—merging neutron stars or a **Hypernova**—have been proposed as the source of gamma-ray bursts.



Neutron Star Binaries: Gamma Ray Bursts

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

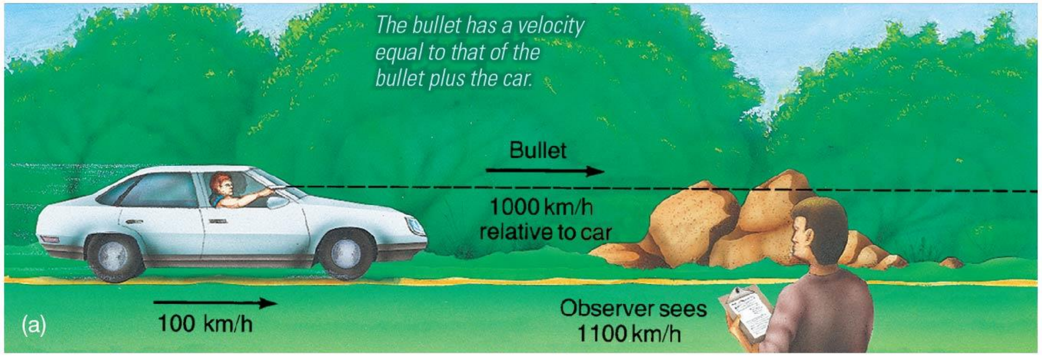


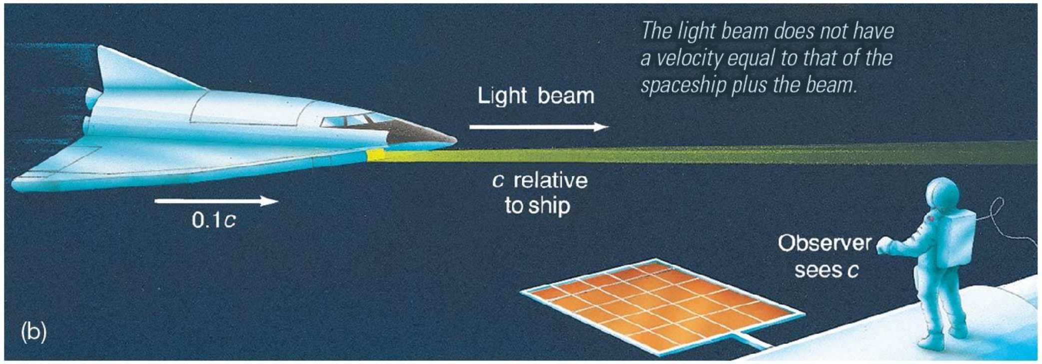
Black Holes

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

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.



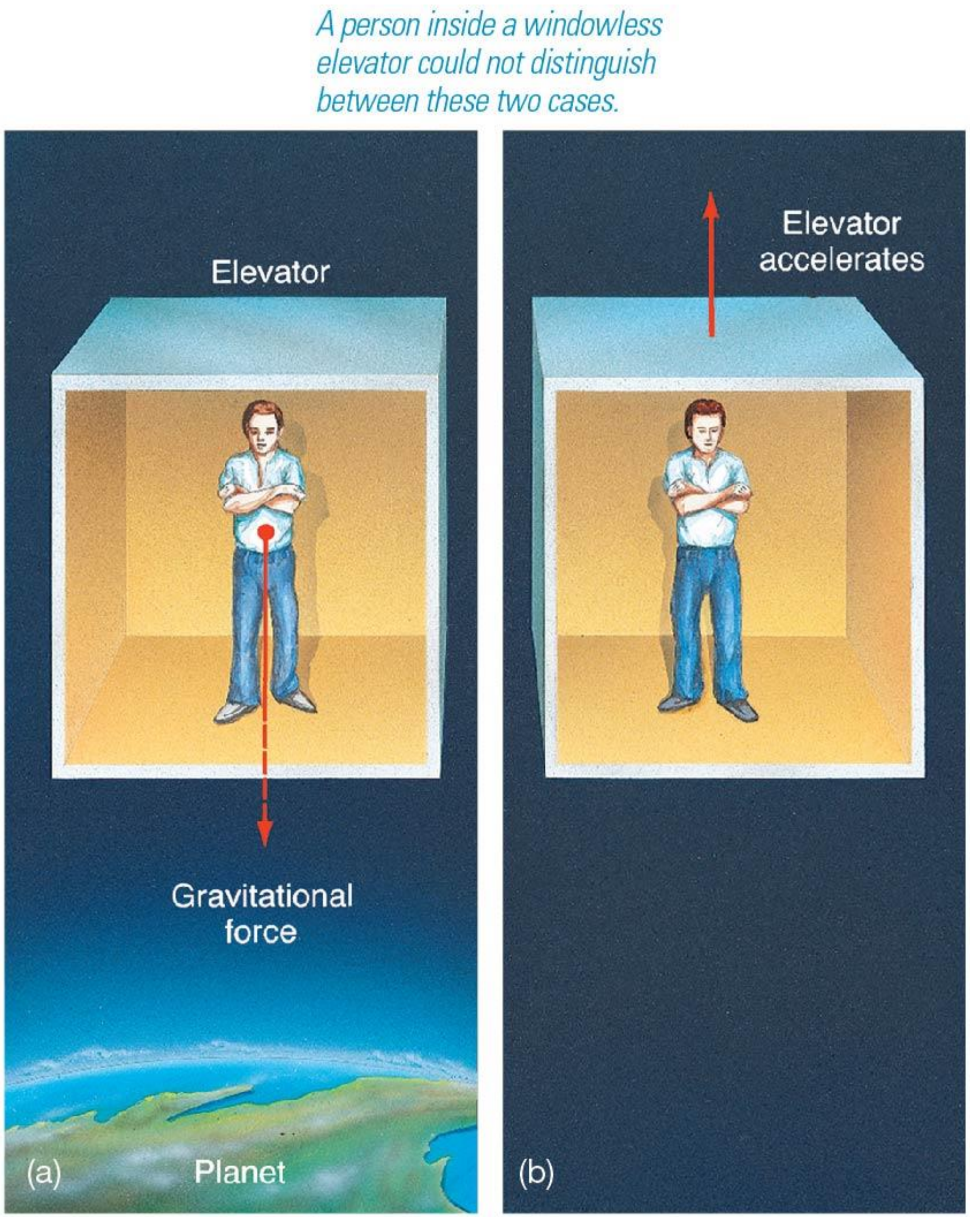


Einstein's Theories of Relativity

2. There is no absolute frame of reference and no absolute state of rest.
3. Space and time are not independent, but rather are unified as space-time.

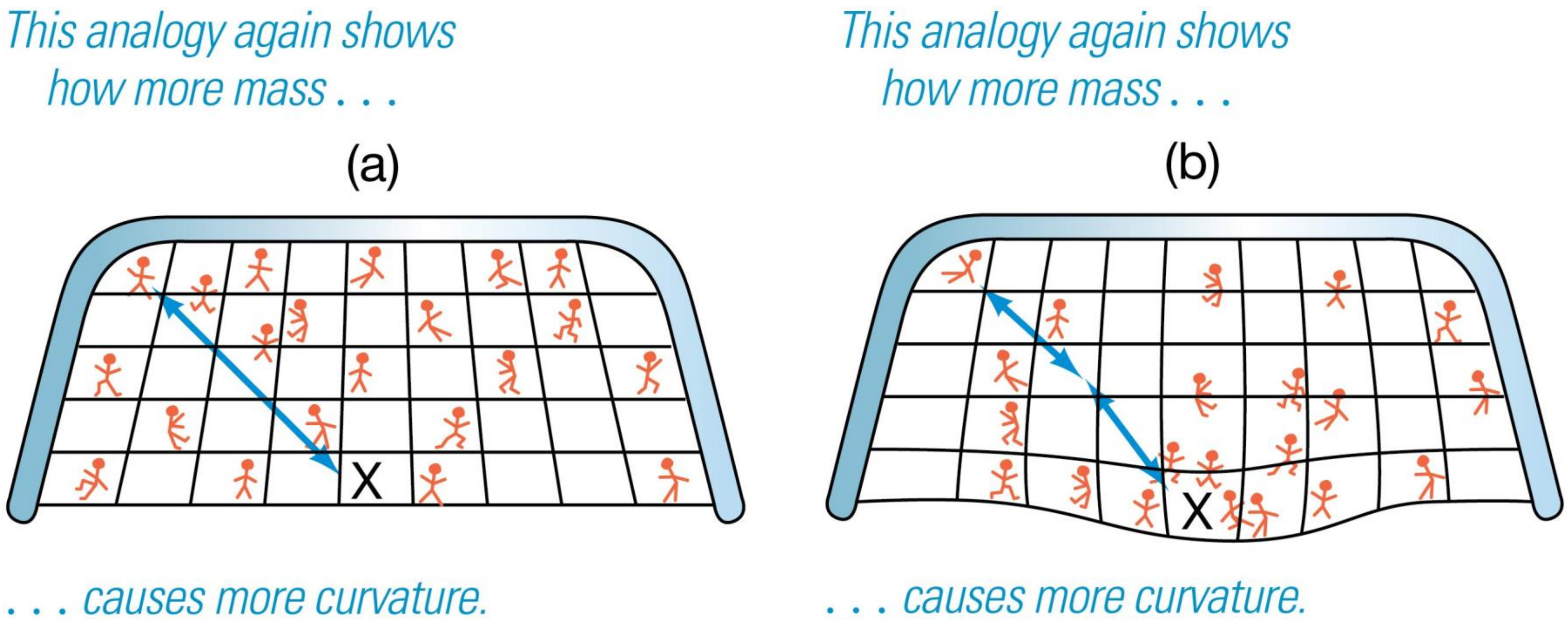
Einstein's Theories of Relativity

- **General relativity**:
  – It is impossible to tell, from within a closed system, whether one is in a gravitational field or accelerating.



Einstein's Theories of Relativity

- Matter tends to warp space-time, 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.

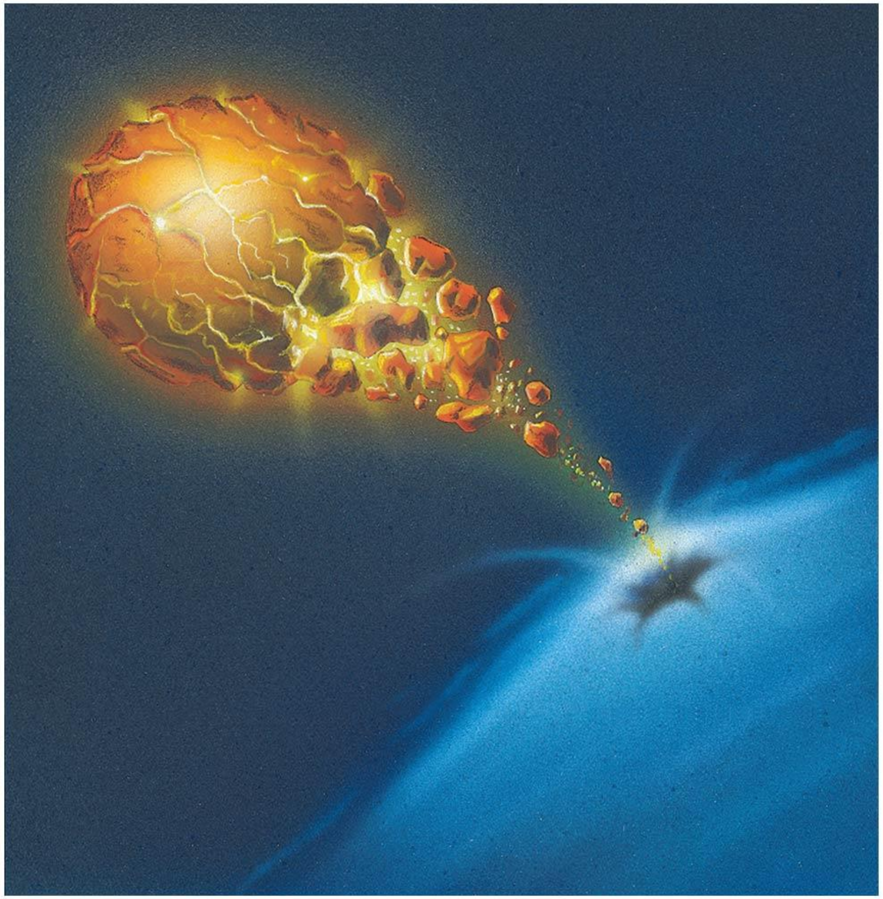


Space Travel Near Black Holes

- 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.

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.

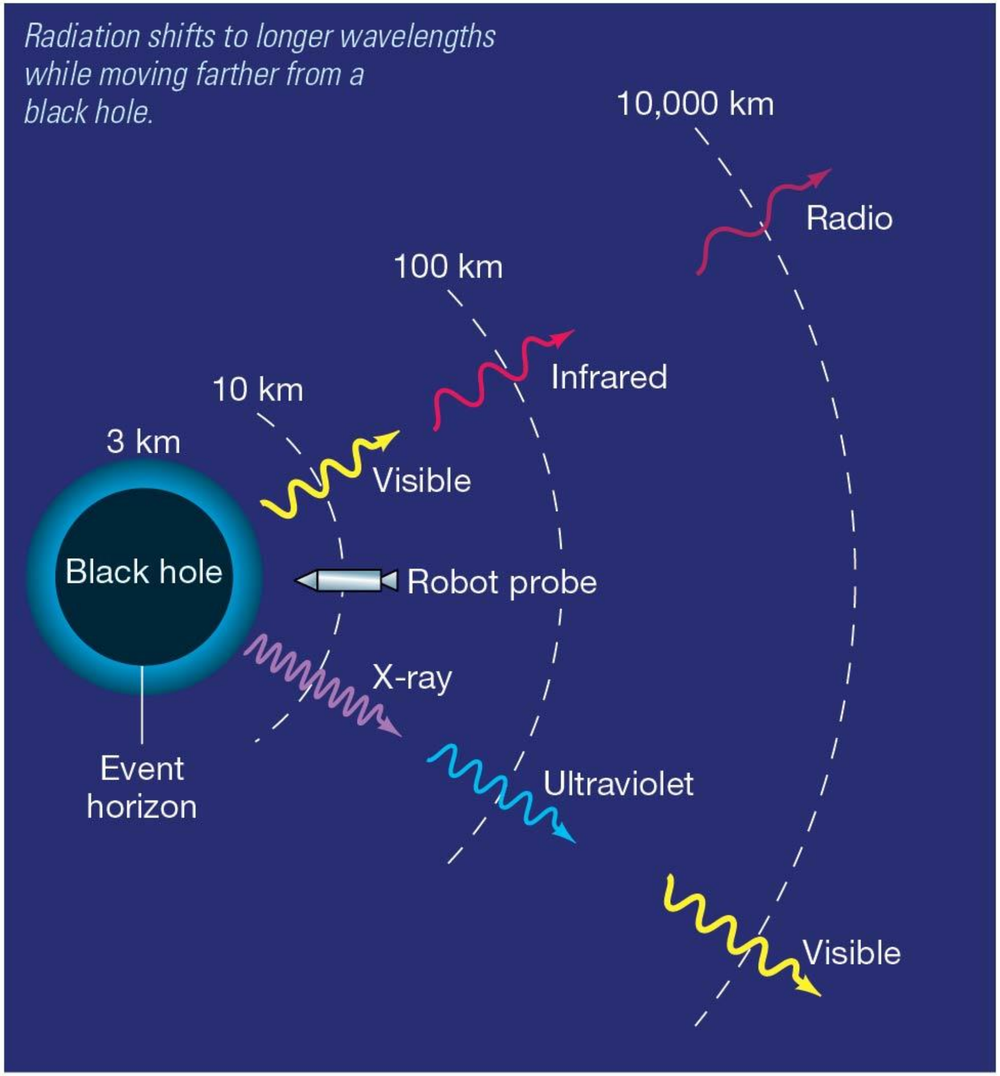


Space Travel Near Black Holes

- 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.

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.

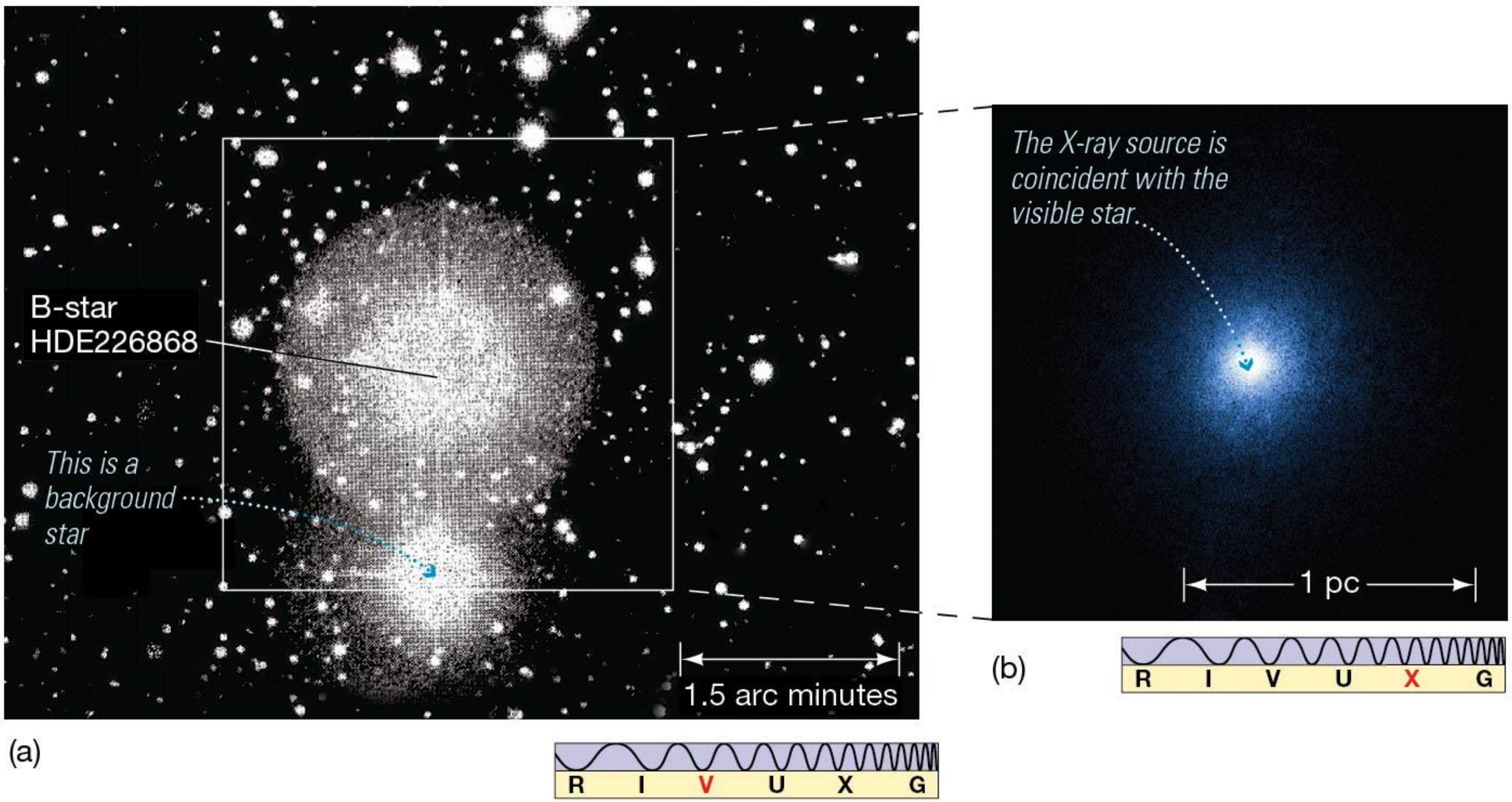


Space Travel Near Black Holes

- **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; 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.

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 in-falling matter.

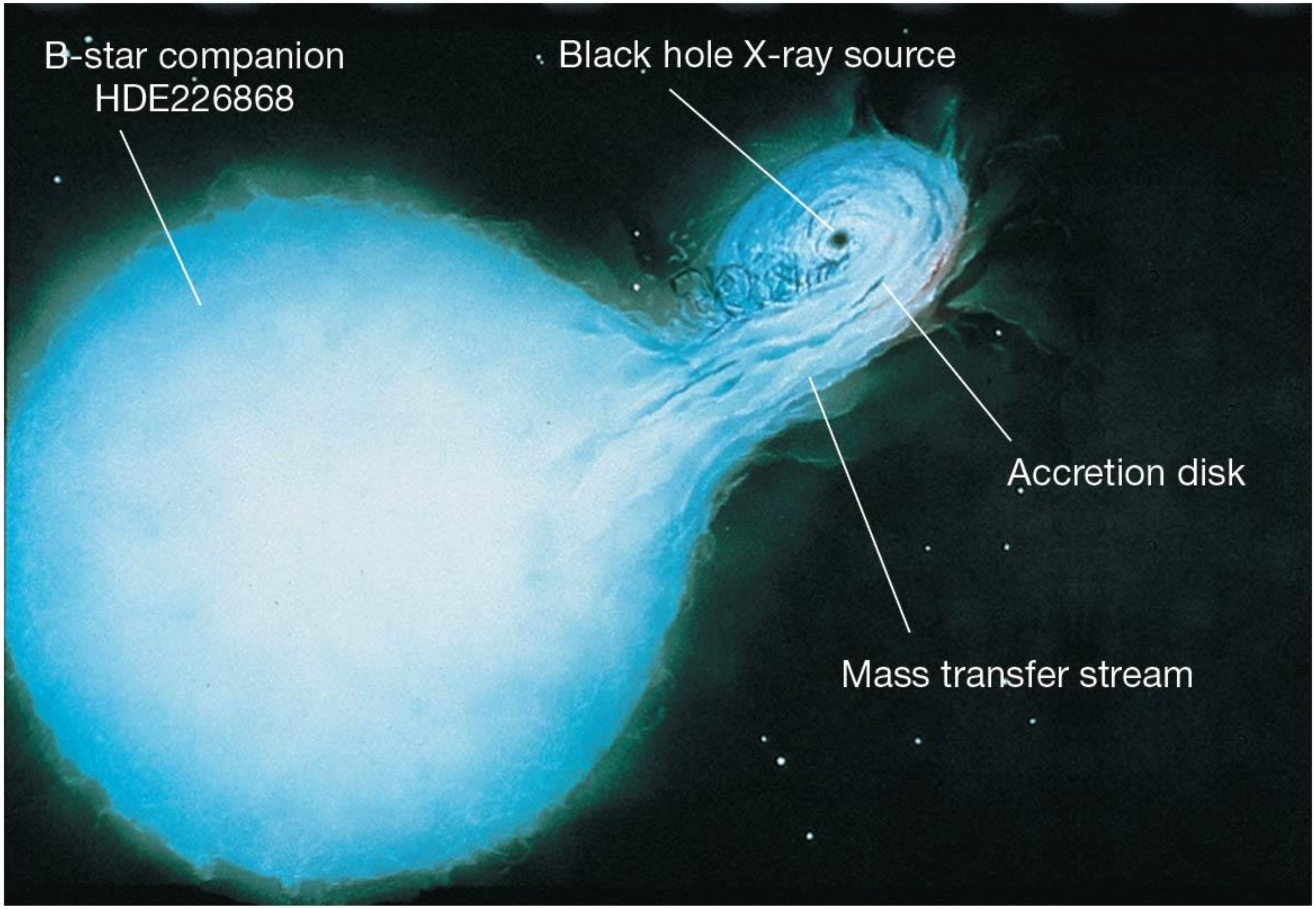


Observational Evidence for Black Holes

- **Cygnus X-1** (1900 pc away) 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 timescale variations indicate that the source must be very small.

Observational Evidence for Black Holes

- Artist's conception of the dynamics of the Cygnus X-1 system

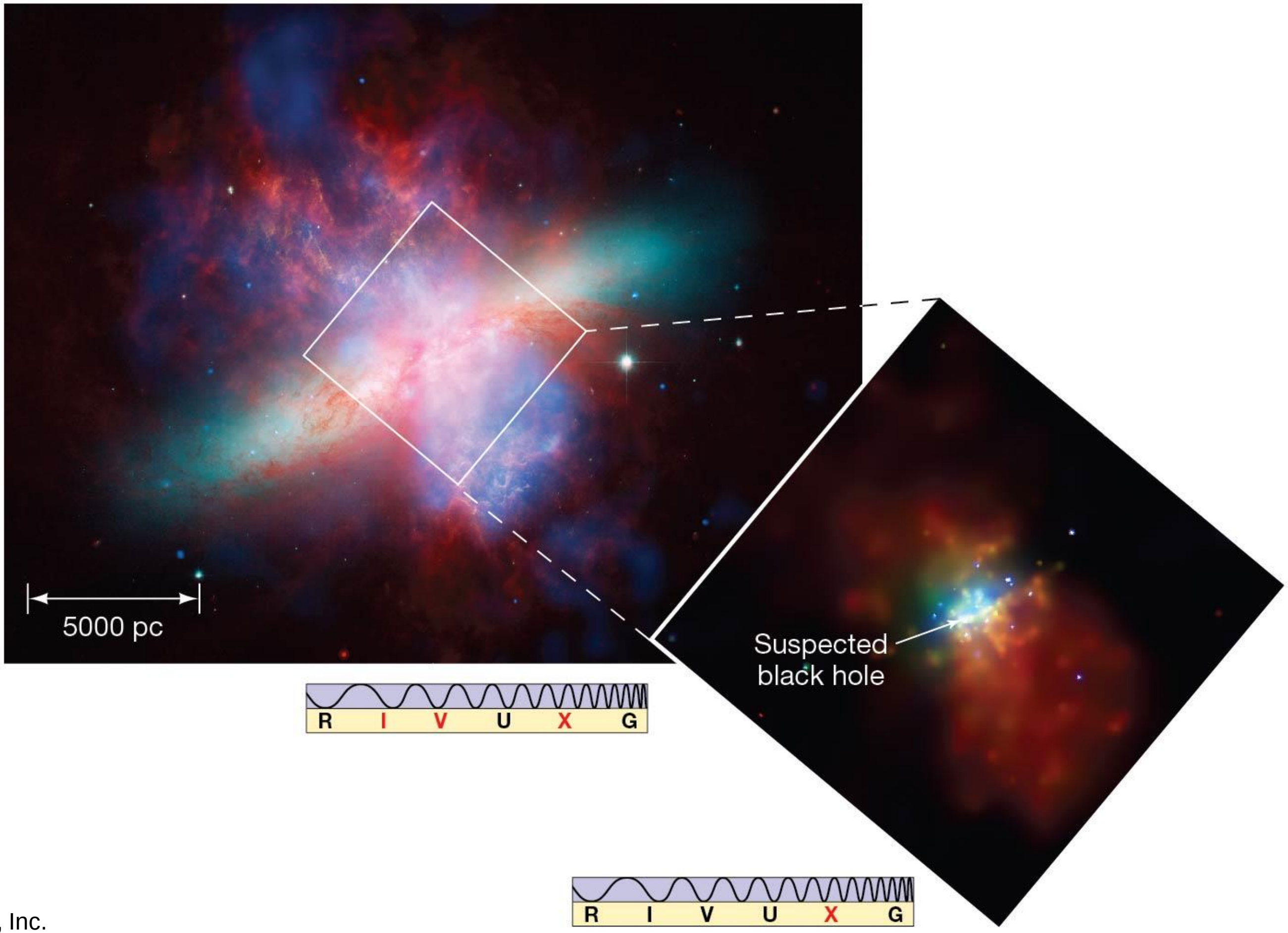


Observational Evidence for Black Holes

- There are several other black hole candidates as well, with characteristics similar to Cygnus X-1.
- The closest is V616 Monocerotis (about 920 pc away) with a mass between 9 – 13 solar masses.
- The centers of many galaxies contain **supermassive black holes**— from millions of solar masses to even billions.
- The center of the Milky Way is thought to have a black hole of about 3.6 million solar masses and lies about 8 kiloparsecs away.
- The galaxy M87 has a mass of about 2.4 billion solar masses and lies about 16.5 megaparsecs away from us.

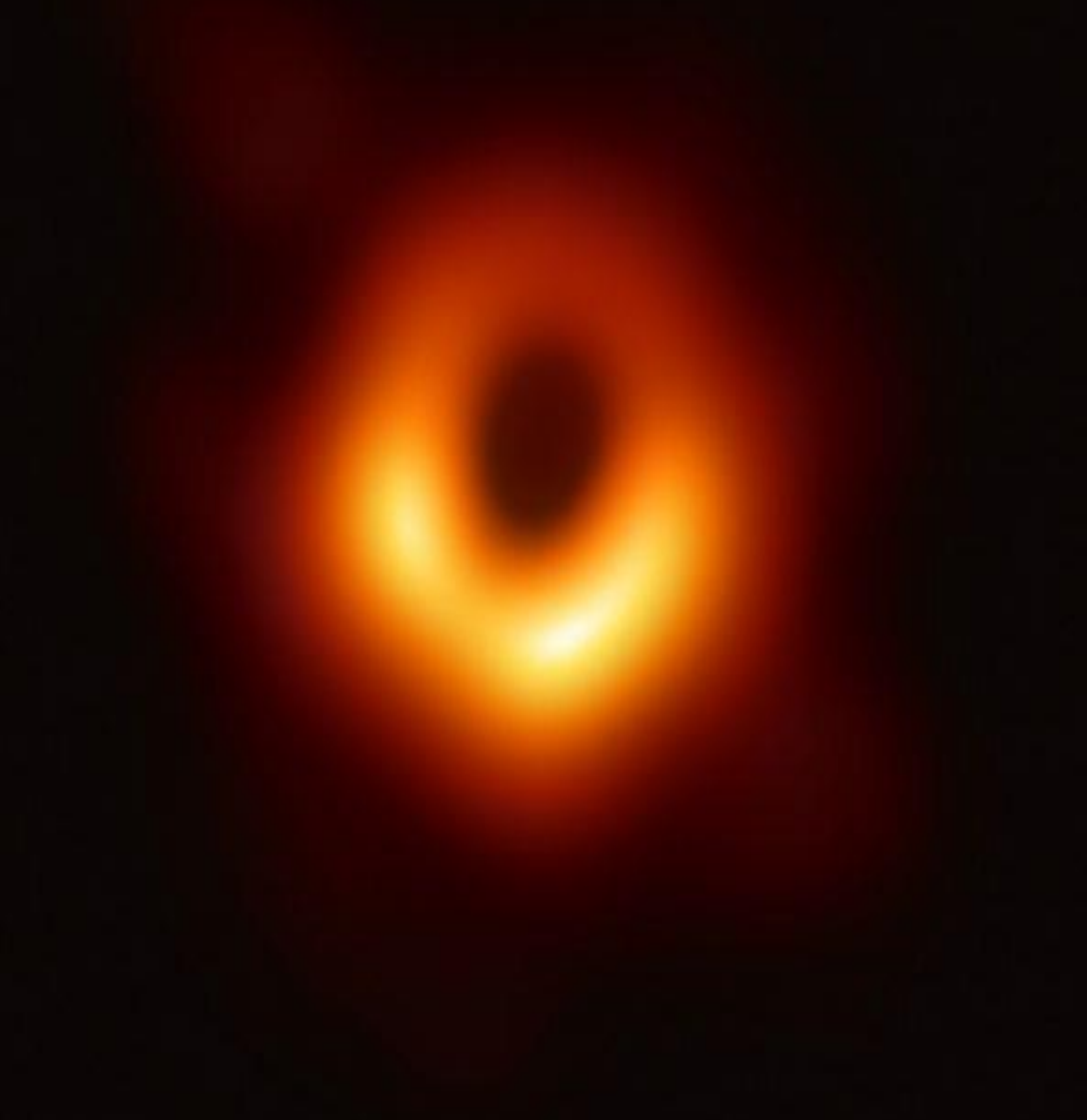
Observational Evidence for Black Holes

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



The Supermassive Black Hole in M87

[Video]



Summary

- A 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 close binary may become an X-ray burster or millisecond pulsar.
- Gamma-ray bursts probably are due to two neutron stars colliding, or to hypernova.

Summary, cont.

- If the core remnant is more than about 3 solar masses, it collapses into a 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.
- Distance from an event horizon to singularity is the Schwarzschild radius.

Summary, cont.

- Distant observer would see an object entering a black hole to be 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.