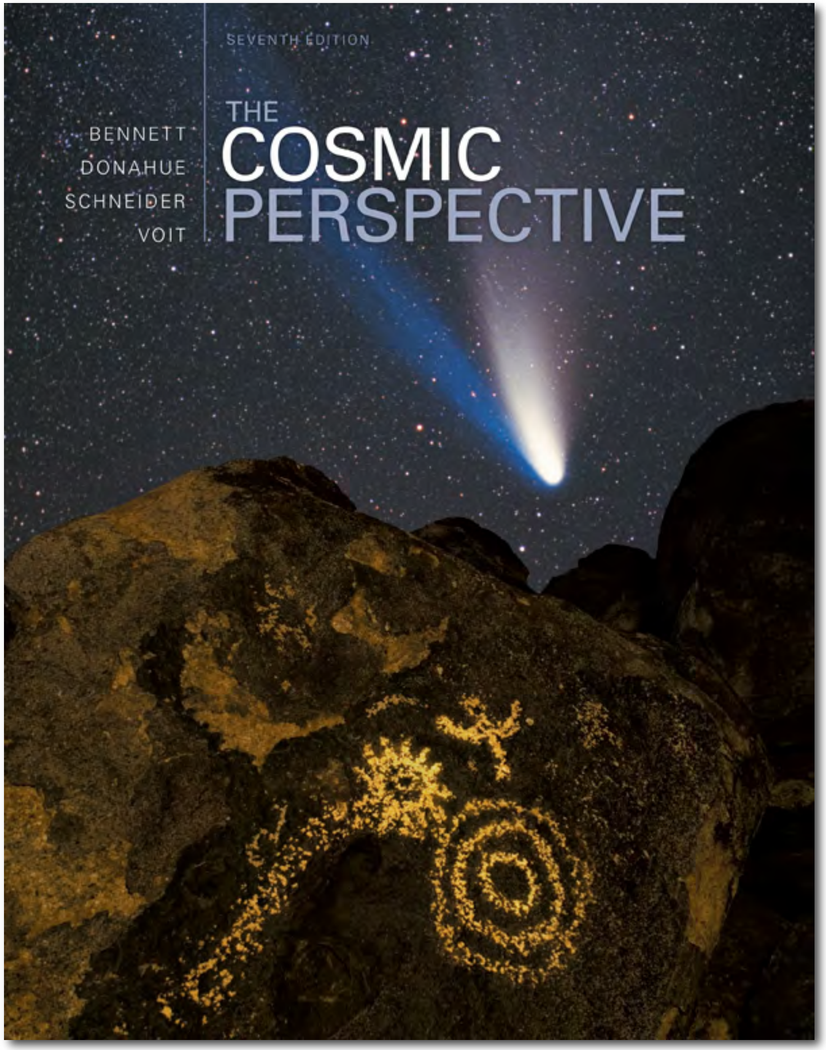
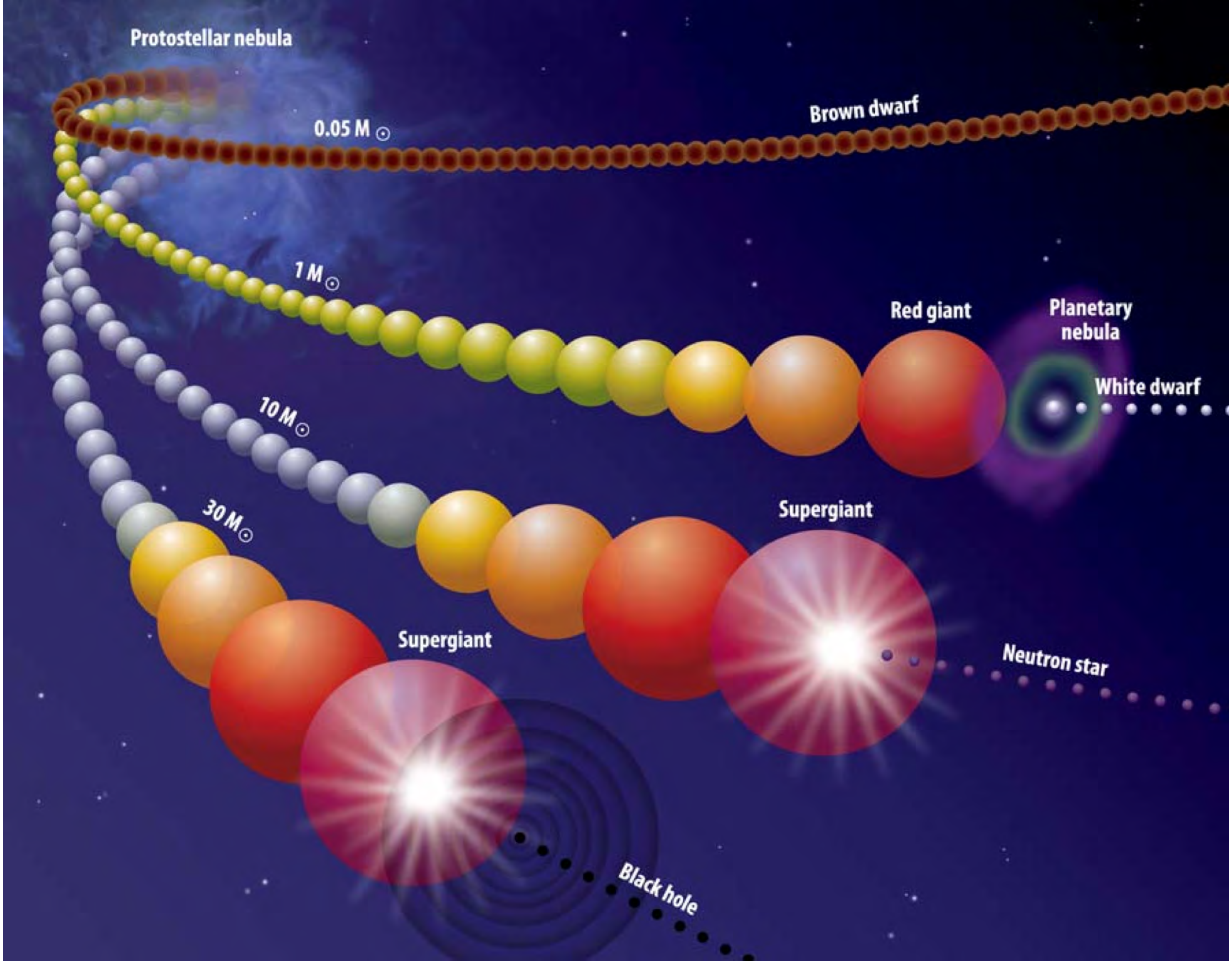
The Cosmic Perspective



The Bizarre Stellar Graveyard


Protostellar nebula
0.05 M ⊙
Brown dwarf
1 M ⊙
Red giant
Planetary nebula
White dwarf
10 M ⊙
30 M ⊙
Supergiant
Supergiant
Neutron star
Black hole

Stellar Remnants

During the course of a stars evolution it will shed a significant fraction of its mass. The mass that is left will determine its fate.

Typically, stars with a initial mass of less than $8M_\odot$ will end up as white dwarfs.

Fate depending on the **mass of the stellar remnant**:

$M_{remnant} < 1.4M_\odot$ => White dwarf
$1.4M_\odot < M_{remnant} < 3M_\odot$ => Neutron star
$M_{remnant} > 3M_\odot$ => Black hole

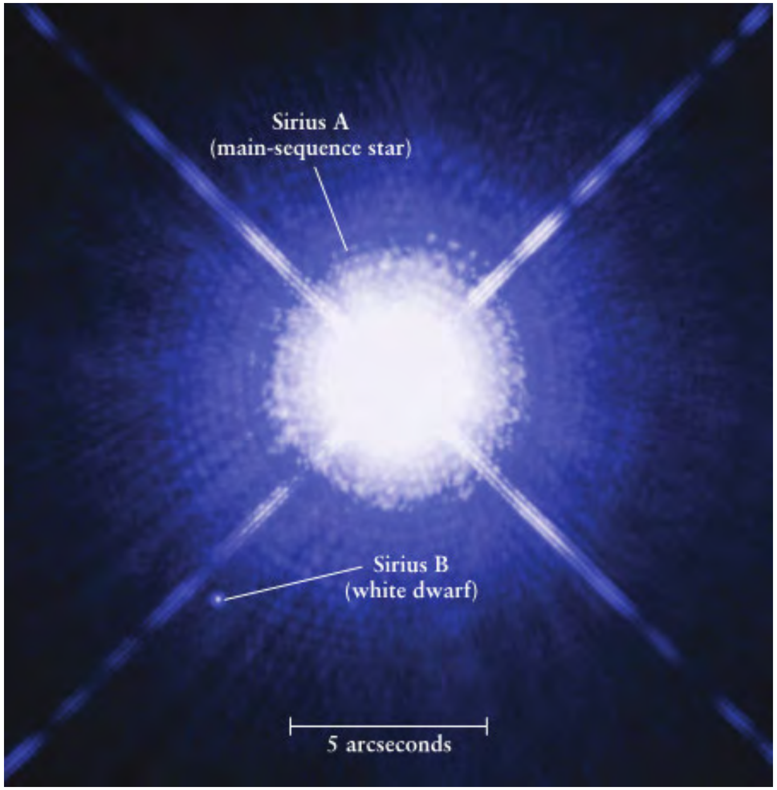
It is estimated that there are ~ 100 million neutron stars and ~1 million black holes in our galaxy.

White Dwarfs

When does a star evolve into a **white dwarf.**?

A star with a mass of
$0.4\ M_{\odot} < M < 4\ M_{\odot}$ after consuming all the H in its core will begin fusing He into C and O.

Such stars do not have high enough temperatures and densities in their cores to fuse C when He runs out in the core and end their life by ejecting the outer layers and leaving behind a hot core of C and O. This relic gradually cools done and is called a white dwarf.



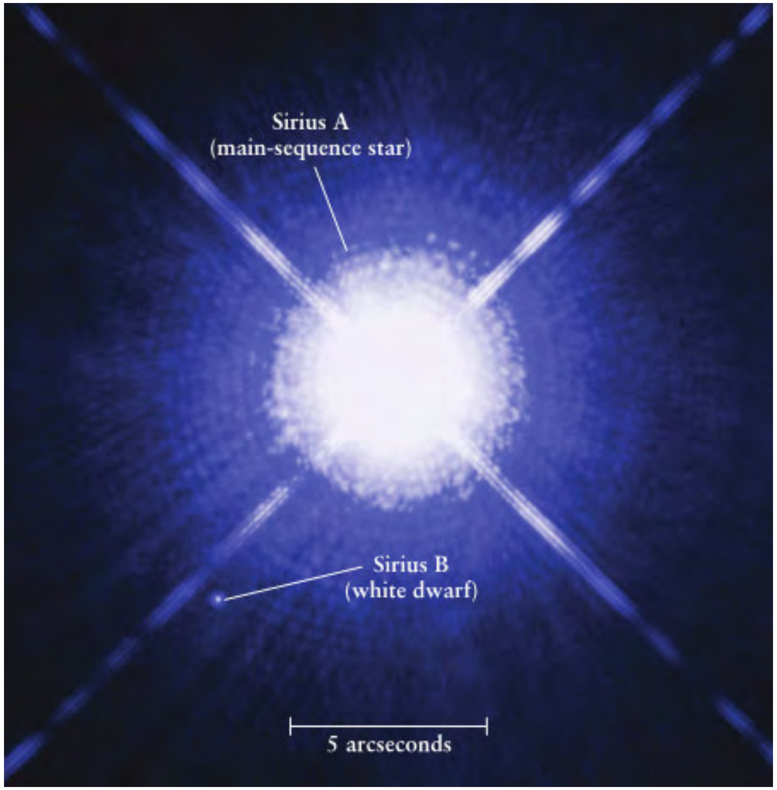
HST image of Sirius and its white dwarf binary companion.

White Dwarfs

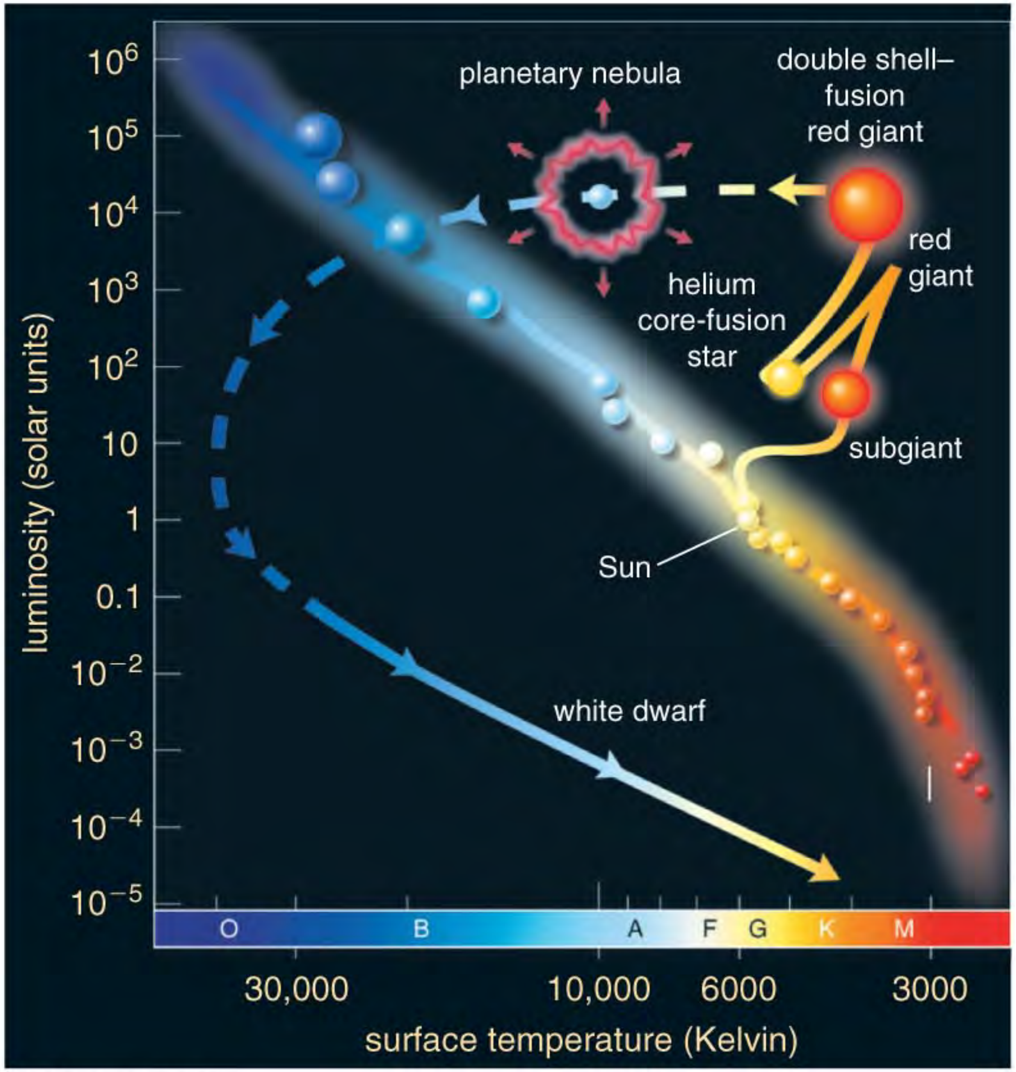
A white dwarf gradually cools down as it radiates away its energy but **does not shrink**. It **is supported by electron degeneracy pressure** against gravitational collapse.

Electron degeneracy pressure does not depend on temperature.

Observations of white dwarfs in binary systems allow us to determine their mass, radius and density. The degenerate electron gas has a density of about $\rho_{WD} \sim 10^9$ kg m^{-3}. For comparison $\rho_{water} \sim 1{,}000$ kg m^{-3}.

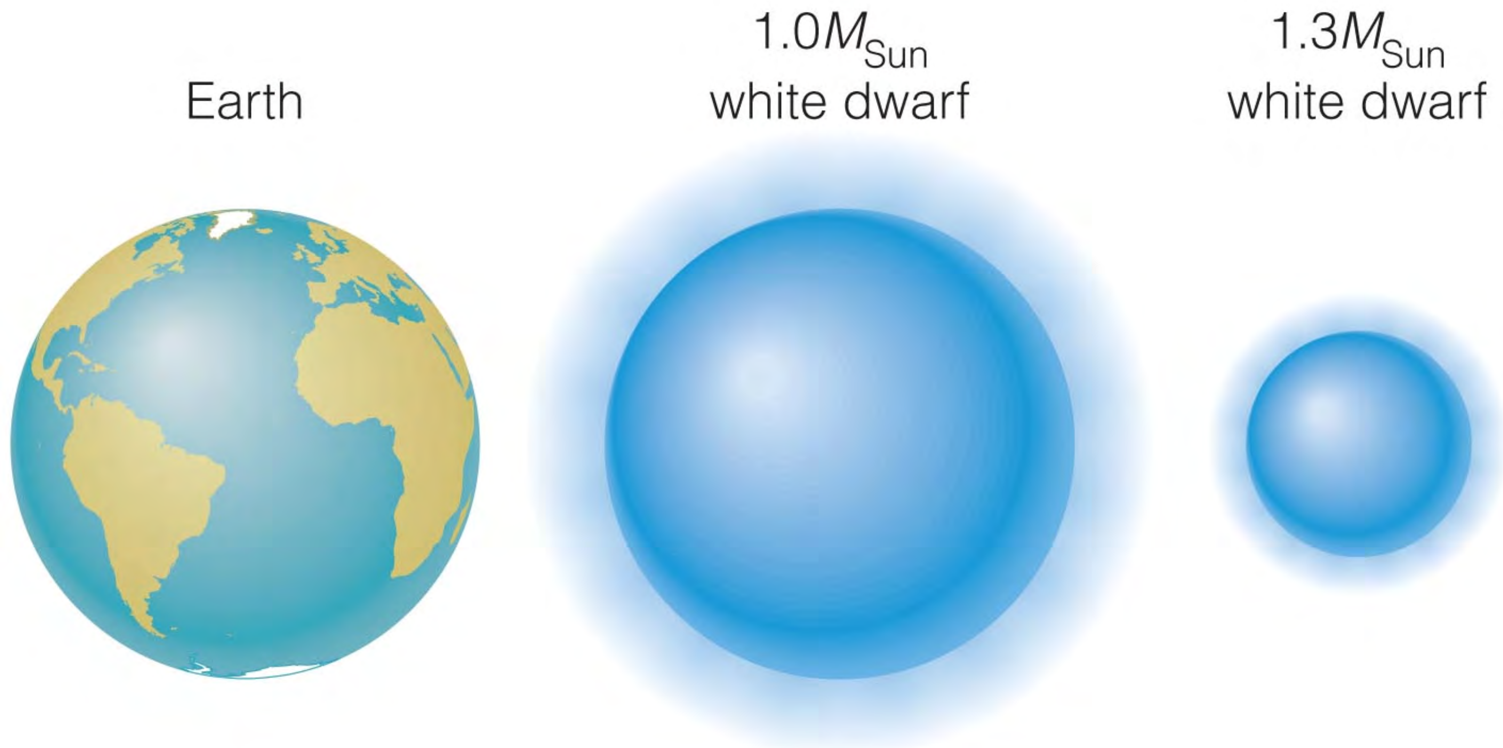


A teaspoon of degenerate electrons from Sirius B brought back to Earth would weigh as much as an elephant.



- White dwarfs cool off and grow dimmer with time.

Size of a White Dwarf

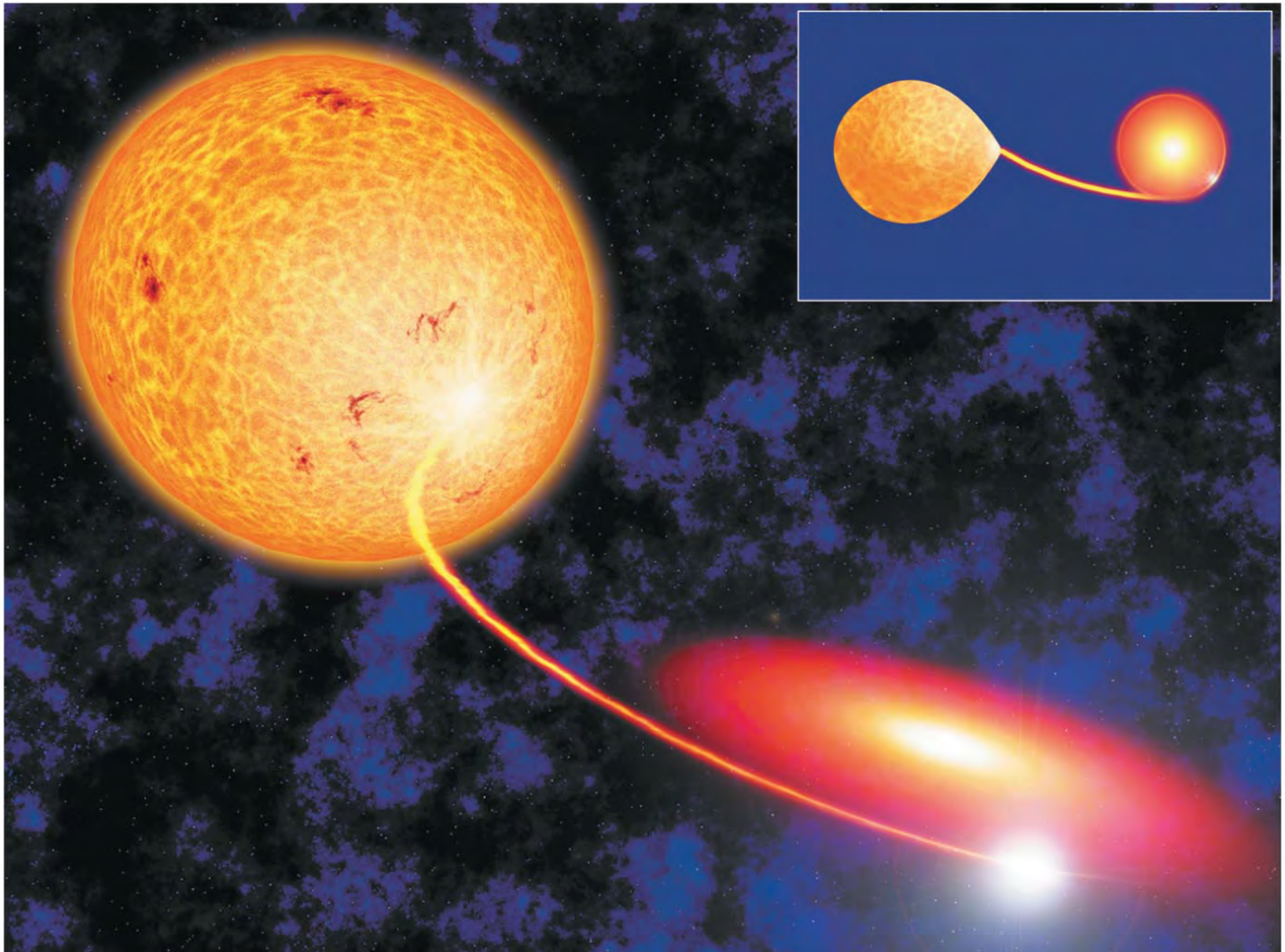


- White dwarfs with same mass as Sun are about same size as Earth.
- Higher-mass white dwarfs are smaller.

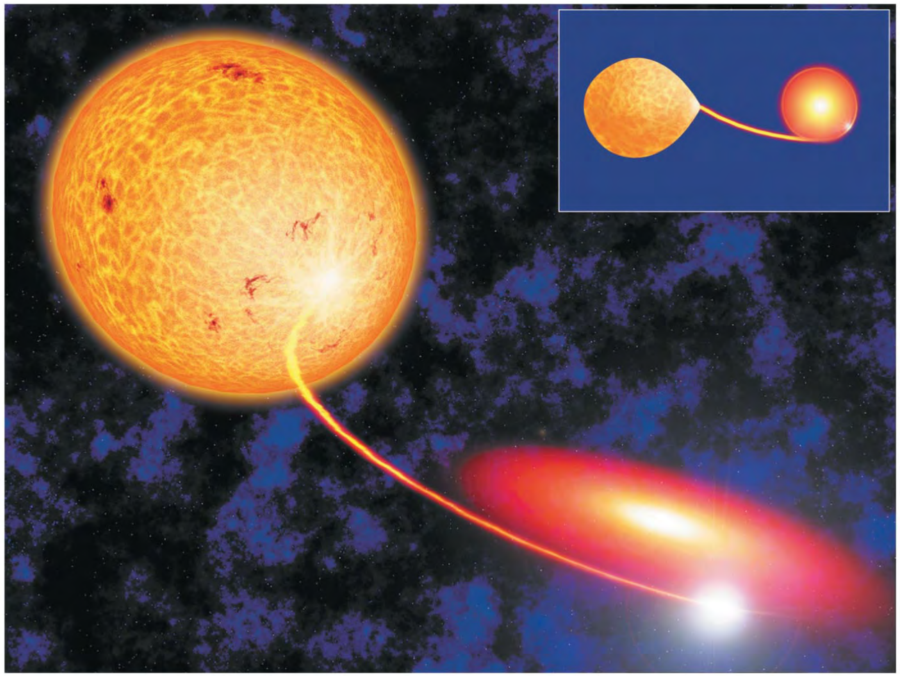
The White Dwarf Limit

- Quantum mechanics says that electrons must move faster as they are squeezed into a very small space.
- As a white dwarf's mass approaches $1.4M_{Sun}$, its electrons must move at nearly the speed of light.
- Because nothing can move faster than light, a white dwarf cannot be more massive than $1.4M_{Sun}$, the *white dwarf limit* (or *Chandrasekhar limit*).

What can happen to a white dwarf in a close binary system?

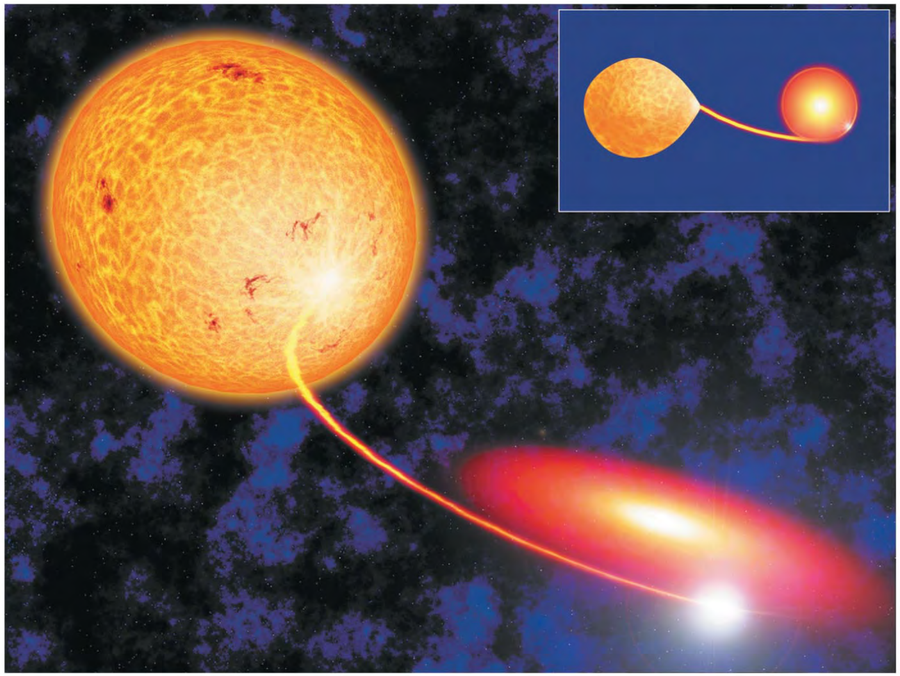


Accretion Disks



- Mass falling toward a white dwarf from its close binary companion has some angular momentum.
- The matter therefore orbits the white dwarf in an *accretion disk*.

Accretion Disks



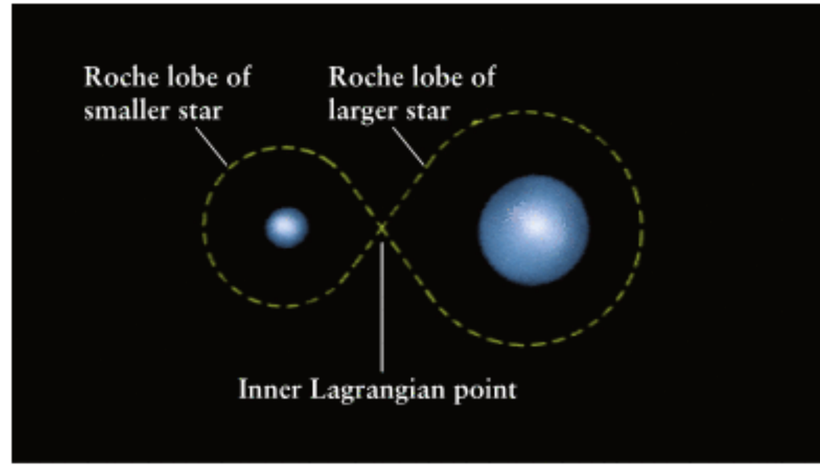
- Friction between orbiting rings of matter in the disk transfers angular momentum outward and causes the disk to heat up and glow.

Accretion Disks

A red giant in a close binary system may transfer mass to its companion star and alter the evolution of both stars.

Roche lobe: A teardrop-shaped volume surrounding a star in a binary inside which gases are gravitationally bound to that star.

If gas from the outer layers of a red giant moves beyond its Roche lobe it is not bound and may be transferred to the companion star.

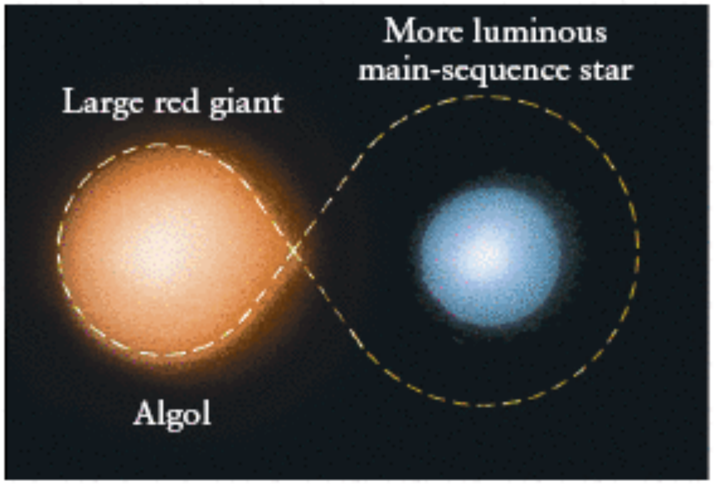


(a) Detached binary: Neither star fills its Roche lobe.

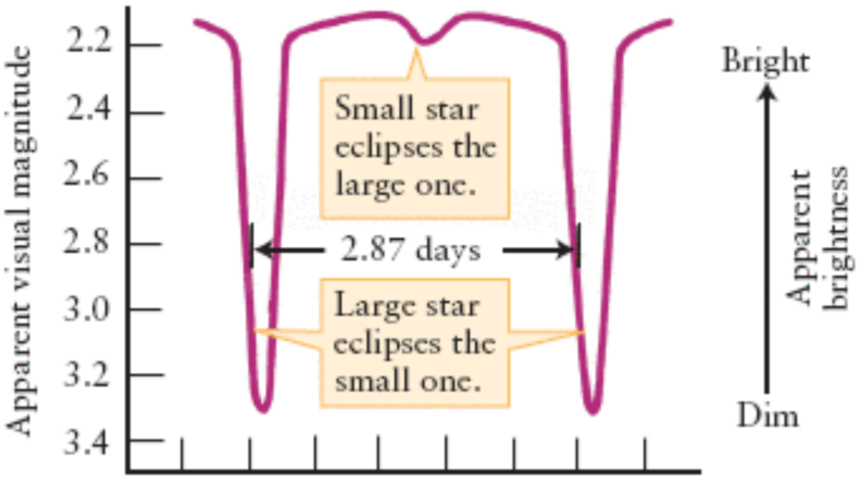
The point where the two Roche lobes touch is called the **inner Lagrangian point.**

If a star does not fill its Roche lobe it is called **detached.**

Algol



(a) A semidetached binary



Algol : an eclipsing close binary with the detached star being more luminous more massive and on the main sequence.

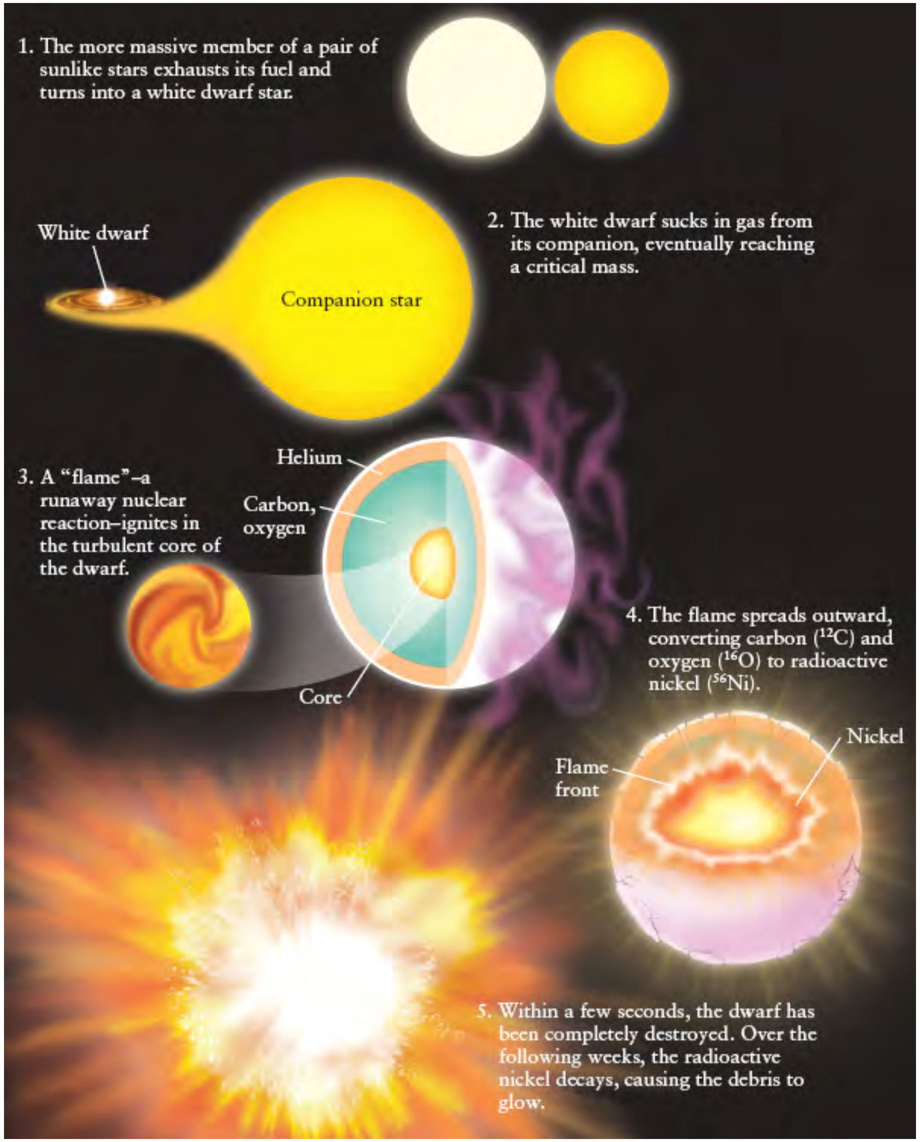
Type Ia Supernova

Type Ia supernovae are thought to result from the thermonuclear explosion of a white dwarf star that is in a binary system with a red giant star.

The white dwarf accretes mass from its companion and eventually the total mass of the white dwarf approaches the *Chandrasekhar limit*.

The increased pressure applied to the white dwarf's interior causes carbon to fuse to silicon in the core resulting in an increase of the core temperature.

Degenerate matter does not expand with increasing temperature and the nuclear reaction rate increases rapidly.



Thought Question

What would the gas in an accretion disk do if there were no friction?

A. It would orbit indefinitely.
B. It would eventually fall in.
C. It would blow away.

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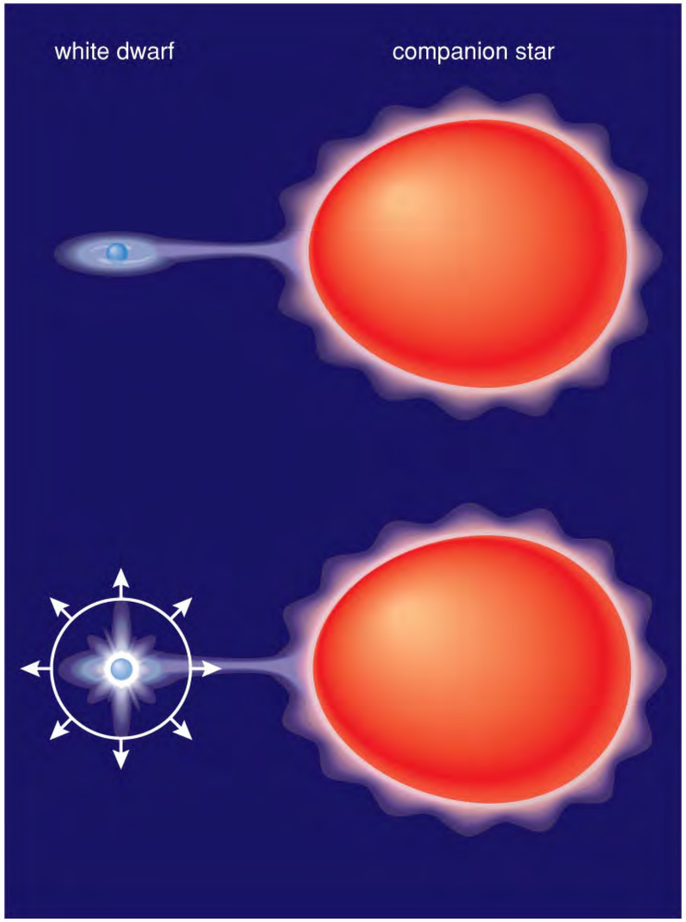
Nova

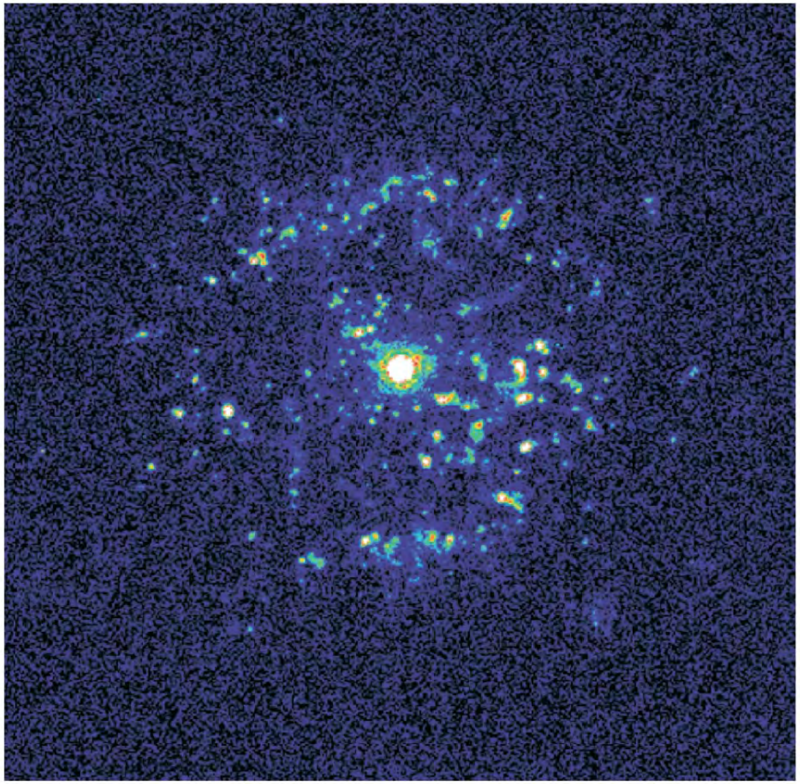


a Diagram of the nova process.

A nova is an explosion that occurs in a binary system comprised of a white dwarf and a companion star overflowing its Roche lobe.

Mass transfer deposits hydrogen on the white dwarf. As the hydrogen is compressed on the surface its temperature rises and when it reaches 10^7 K fusion of hydrogen begins.

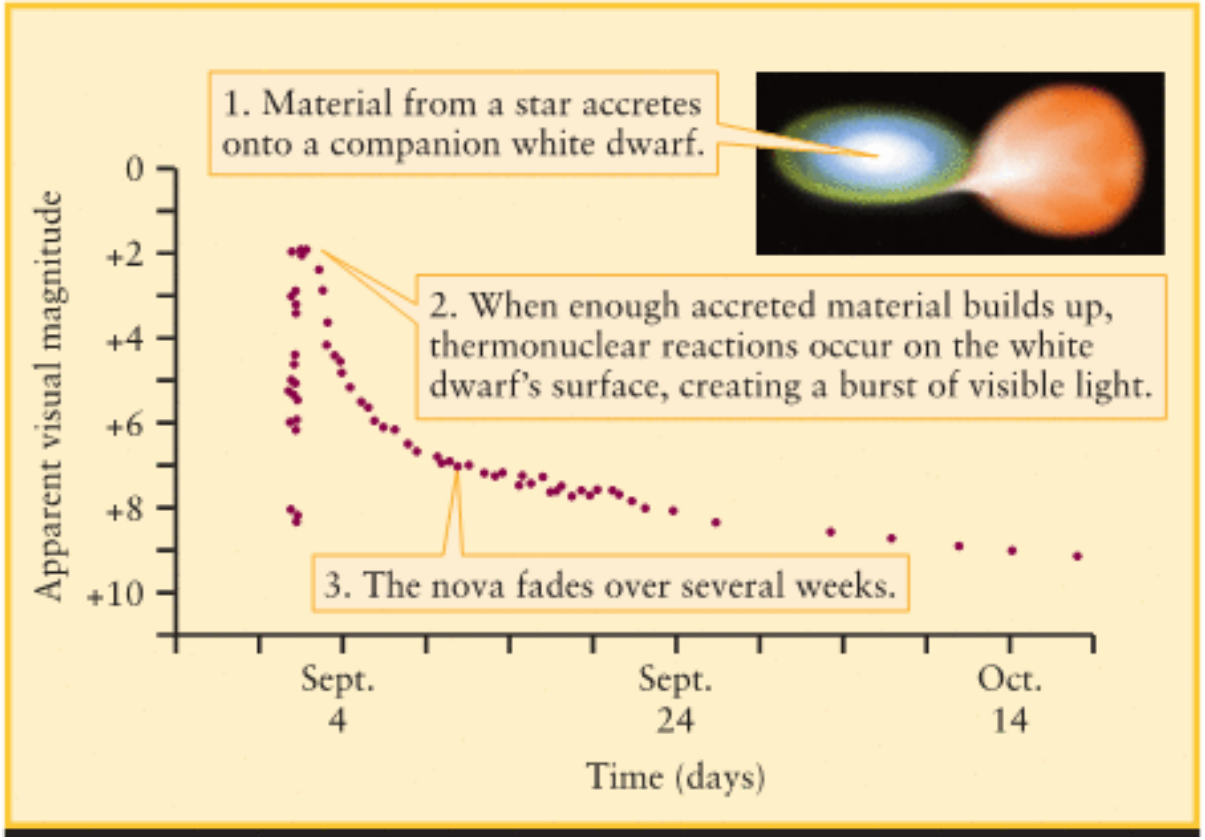
Nova



b Hubble Space Telescope image showing blobs of gas ejected from the nova T Pyxidis. The bright spot at the center of the blobs is the binary star system that generated the nova.

- The nova star system temporarily appears much brighter.
- The explosion drives accreted matter out into space.

Nova



The **fusion of hydrogen in degenerate matter** on the white dwarf's surface results in a reaction rate that increases very rapidly creating **a burst of visible light**. The optical brightness may increase by a factor of 10^4 to 10^8 reaching a peak luminosity of $\sim 10^5\ L_\odot$.

Thought Question

What happens to a white dwarf when it accretes enough matter to reach the $1.4M_{\text{Sun}}$ limit?

A. It explodes.

B. It collapses into a neutron star.

C. It gradually begins fusing carbon in its core.

Thought Question

What happens to a white dwarf when it accretes enough matter to reach the $1.4M_{\text{Sun}}$ limit?

A. It explodes.

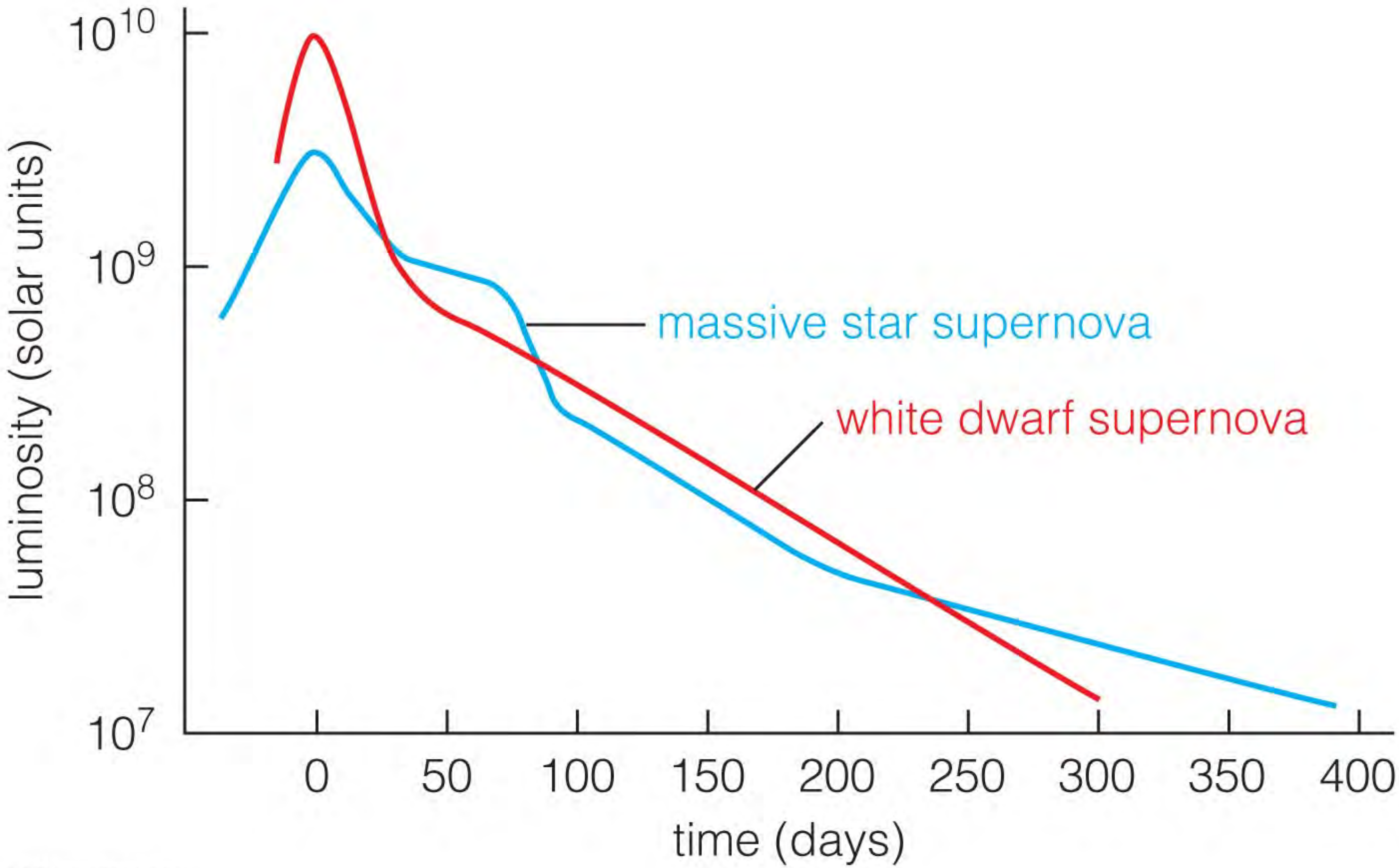
B. It collapses into a neutron star.

C. It gradually begins fusing carbon in its core.

Two Types of Supernova

- ***Massive star supernova (SN type II, type Ib, Ic):***
  - Iron core of a massive star reaches white dwarf limit and collapses into a neutron star or black hole, causing total explosion.

- ***White dwarf supernova (SN type Ia):***
  - Carbon fusion suddenly begins as a white dwarf in close binary system reaches the white dwarf limit, causing total explosion.



- One way to tell supernova types apart is with a ***light curve*** showing how luminosity changes with time.

Nova or Supernova Ia?

- Supernovae type Ia are MUCH MUCH more luminous than novae (about 100 thousand times)!!!
- Nova: H to He fusion of a layer of accreted matter, white dwarf left intact
- Supernova type Ia: complete explosion of white dwarf, nothing left behind

Supernova Type: Massive Star or White Dwarf?

- Light curves differ.
- Spectra differ (exploding white dwarfs don't have hydrogen absorption lines).

Supernova Classification:

Supernovae classification based on spectra:

(1) Supernovae with bright hydrogen emission lines are called **Type II supernovae** and are the result of the core collapse of a highly evolved massive star that still has a lot of hydrogen in its atmosphere when it explodes.

(2) Type I Supernovae have no hydrogen lines in their spectra.

Supernova Classification:

Type Ia SN: Accretion onto a white dwarf from a companion star leads to the explosion of the white dwarf. **No hydrogen** lines are detected in the spectra of type Ia but strong absorption from ionized Si is detected.

Type Ib SN: Core collapse of evolved massive star that has lost most of its hydrogen atmosphere from a stellar wind or by mass transfer to a binary companion.
No H lines but strong He absorption lines are detected.

Type Ic SN: . Core collapse of evolved massive star that has lost most of its hydrogen and helium atmosphere from a stellar wind or by mass transfer to a binary companion.
No H lines and no He lines are detected.

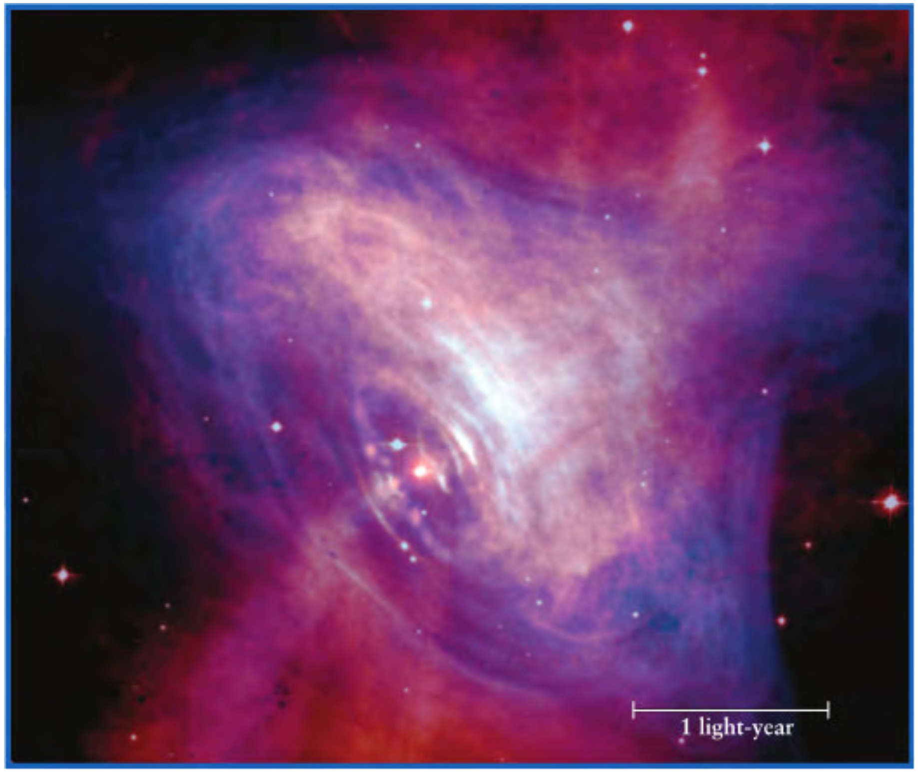
What have we learned?

- **What is a white dwarf?**
  - A white dwarf is the inert core of a dead star.
  - Electron degeneracy pressure balances the inward pull of gravity.
- **What can happen to a white dwarf in a close binary system?**
  - Matter from its close binary companion can fall onto the white dwarf through an accretion disk.
  - Accretion of matter can lead to novae and white dwarf supernovae.

18.2 Neutron Stars

- Our goals for learning:
  - **What is a neutron star?**
  - **How were neutron stars discovered?**
  - **What can happen to a neutron star in a close binary system?**

What is a neutron star?



Fate depending on the **mass of the stellar remnant**:

$M_{remnant} < 1.4M_\odot$ => White dwarf
$1.4M_\odot < M_{remnant} < 3M_\odot$ => Neutron star
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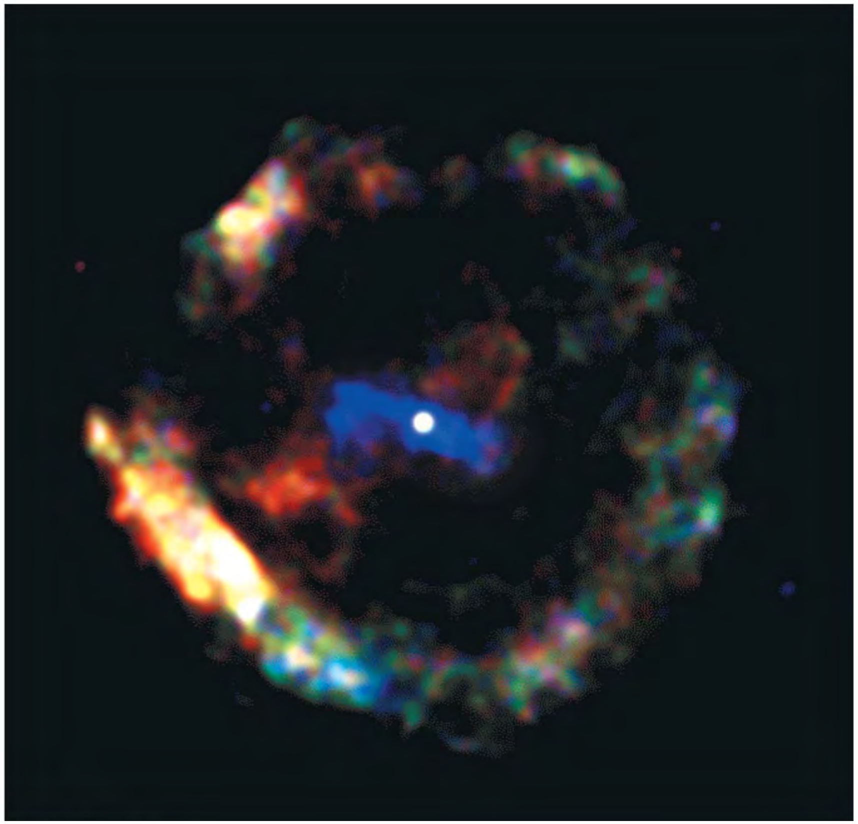
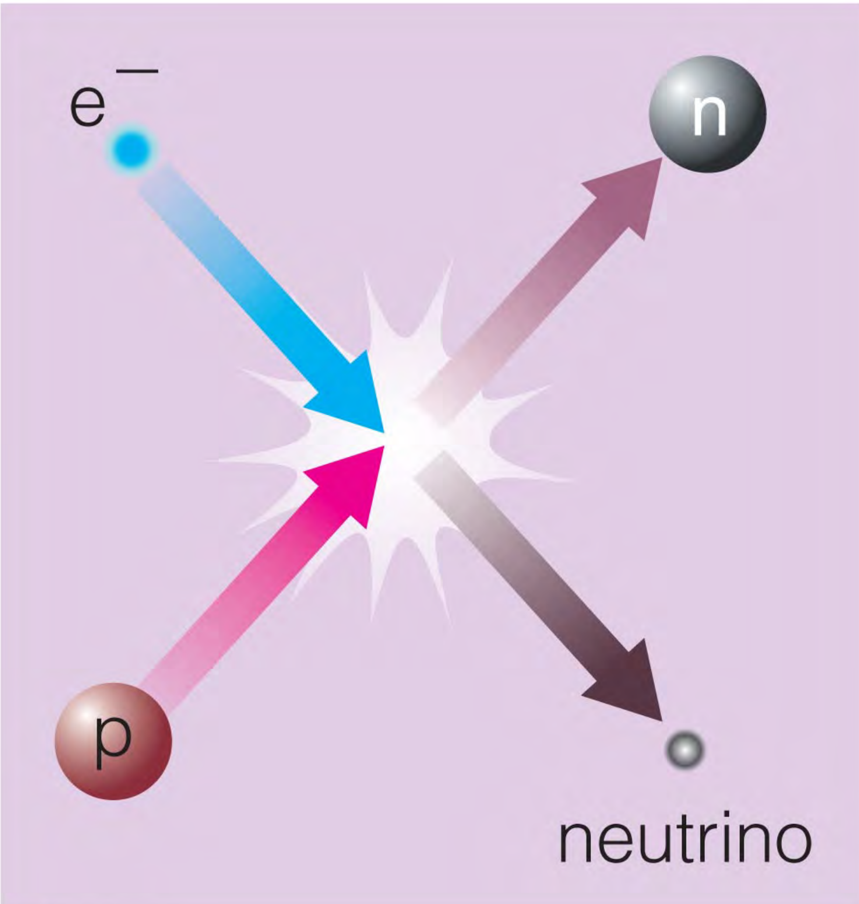


- A neutron star is the ball of neutrons left behind by a massive-star supernova.
- Degeneracy pressure of neutrons supports a neutron star against gravity.



- Electron degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos.

- Neutrons collapse to the center, forming a ***neutron star.***

Neutron Stars

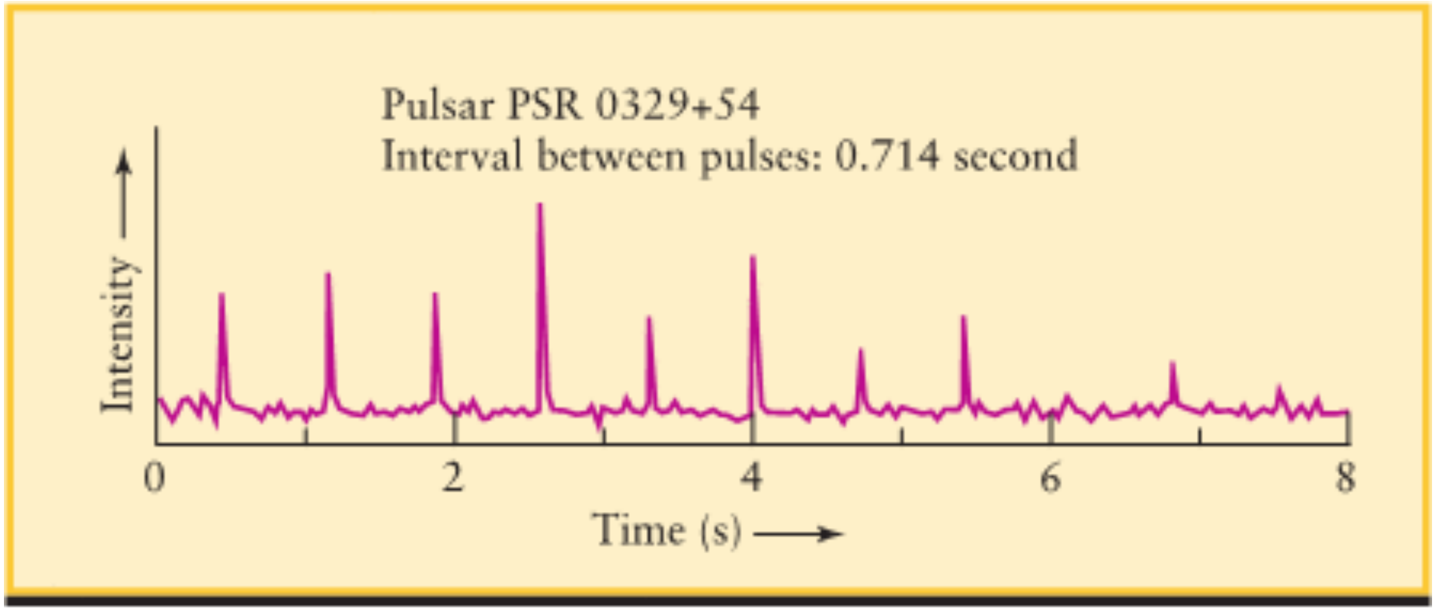
The emission from the supernova that produced the **crab nebula** was observed in **1054 AD** by Chinese, Japanese, Native Americans, and Persian/Arab astronomers as being bright enough in the night sky for almost 2 years.

We now know that **SN 1054 was a Type II supernova** that ended the life of a massive star and left behind a neutron star.

English physicist James Chadwick discovered the neutron in 1932. The neutron is a subatomic particle with a mass similar to that of a proton and with no electric charge.

Astronomers Zwicky and Baade first suggested that the collapse of a massive star could lead to an object made up primarily of neutrons (neutron star).

Discovery of Neutron Stars



- Using a radio telescope in 1967, Jocelyn Bell noticed very regular pulses of radio emission coming from a single part of the sky.
- The pulses were coming from a spinning neutron star—a *pulsar.*

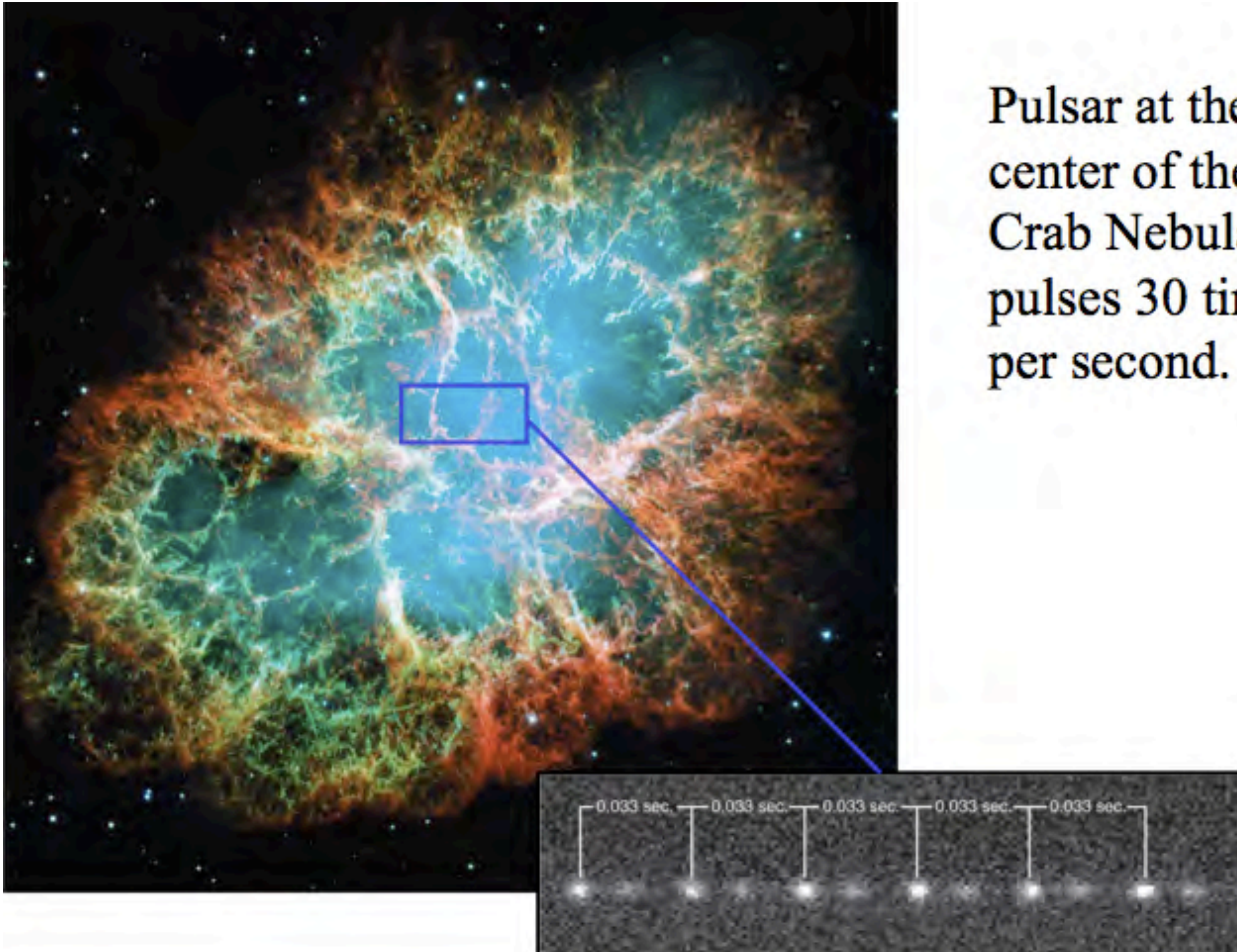
Neutron Stars

Pulsars are just rotating neutron stars.

The neutron star spins up when it forms during the collapse of a spinning star. (a figure skater on ice can increase spin by bringing in their arms).

One year after the discovery of the first pulsar the **central object in the Crab** nebular was found to be **pulsating at ~30 times a second**.

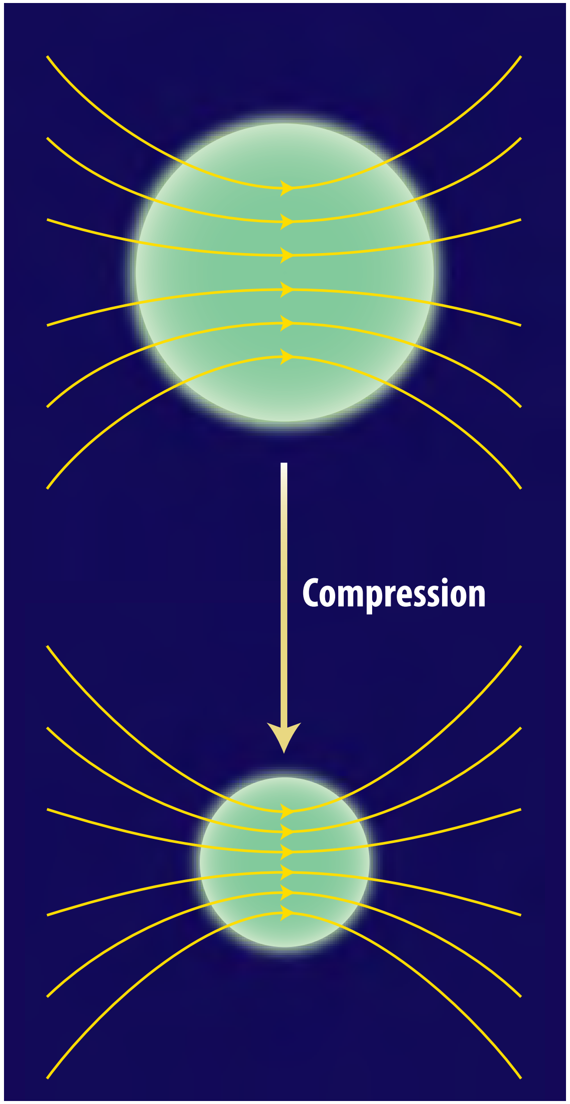
The spinning neutron star in the middle of the Crab nebula explained the origin of its glow. The energy source of its glow is the rotational energy of the neutron star.



Pulsar at the center of the Crab Nebula pulses 30 times per second.

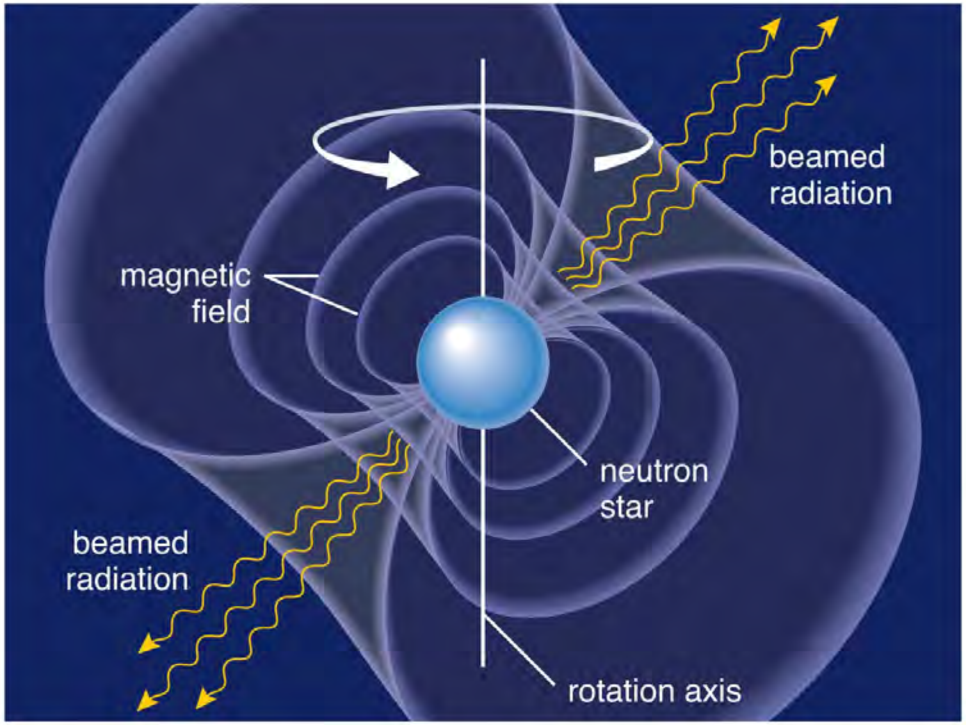
Properties of Neutron Stars

As the star collapses, the plasma drags the magnetic field lines with it (surface area shrinks by a factor of 10^{10}). This implies that the magnetic field of a NS would be at least 10^{10} times larger than that of the ordinary star from which it collapsed from.



Earth's magnetic field ~ 0.5 Gauss
WD magnetic field ~ 10^6 Gauss
NS magnetic field ~10^{12-15} Gauss

Pulsars



- A ***pulsar*** is a neutron star that beams radiation along a magnetic axis that is not aligned with the rotation axis.

Pulsars

- The radiation beams sweep through space like lighthouse beams as the neutron star rotates.

Why Pulsars Must Be Neutron Stars

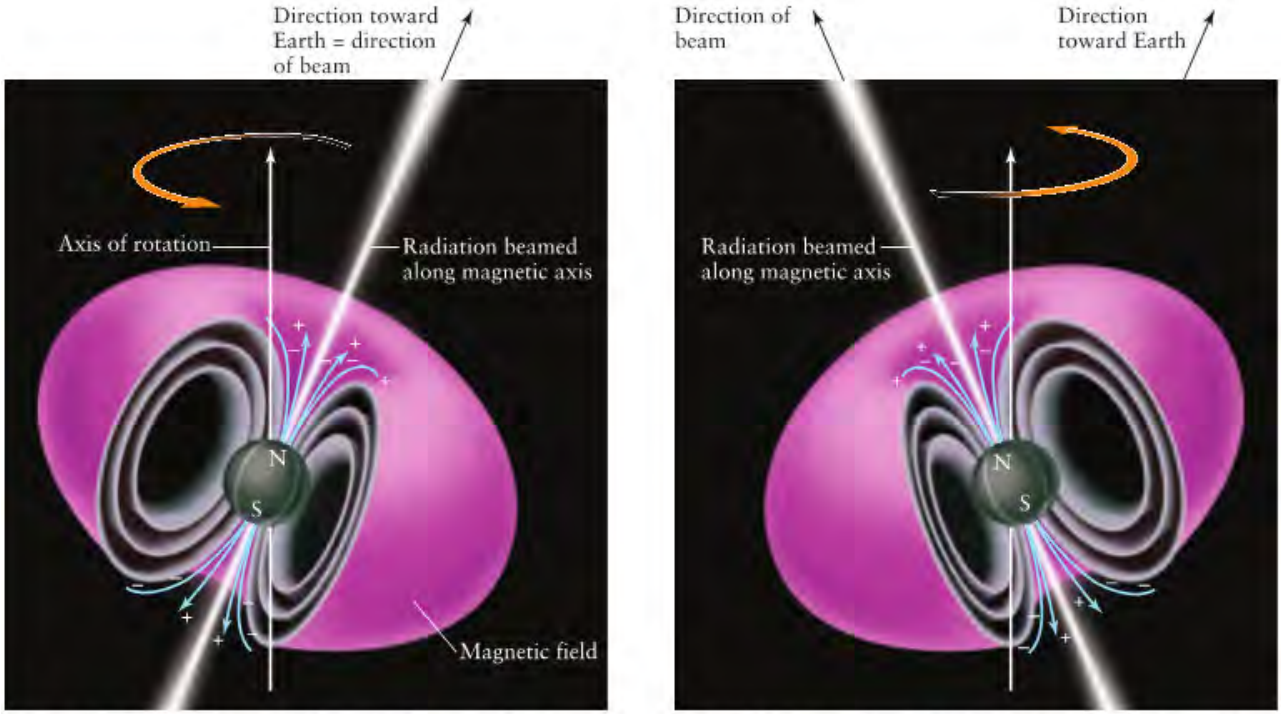
Circumference of NS = 2π (radius) ~ 60 km

Spin rate of fast pulsars ~ 1000 cycles per second

– Surface rotation velocity ~ 60,000 km/s
~ 20% speed of light
~ escape velocity from NS

Anything else would be torn to pieces!

Why is radiation beamed from a pulsar?

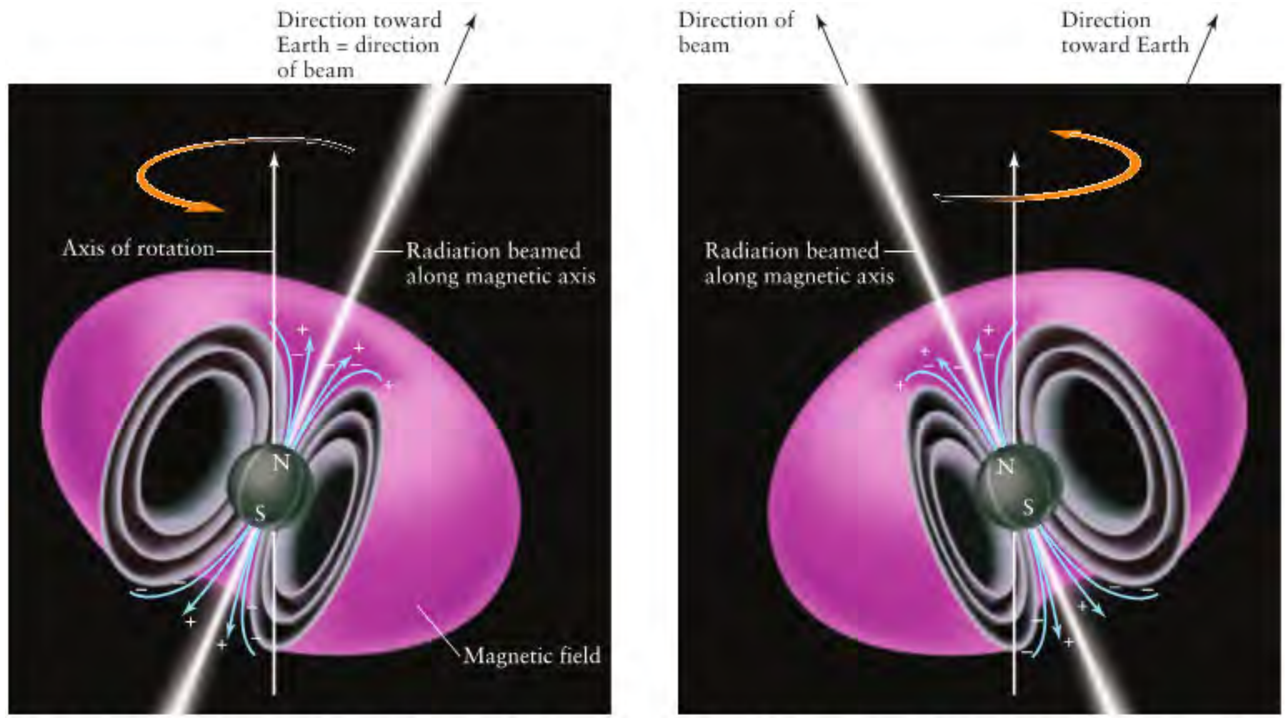


(a) One of the beams from the rotating neutron star is aimed toward Earth: we detect a pulse of radiation.

(b) Half a rotation later, neither beam is aimed toward Earth: we detect that the radiation is "off."

The neutron star's magnetic axis is titled with respect to its rotational axis. The **rotating magnetic fields create electric fields**. The strong electric field near the poles accelerates electrons and ions from the neutron star's surface to near relativistic speeds. As these fast electrons spiral around magnetic field lines they are accelerated and emit synchrotron radiation in the form of gamma rays. Because of the relativistic e^- velocities the gamma rays are beamed along the poles.

Why is radiation beamed from a pulsar?



(a) One of the beams from the rotating neutron star is aimed toward Earth: we detect a pulse of radiation.

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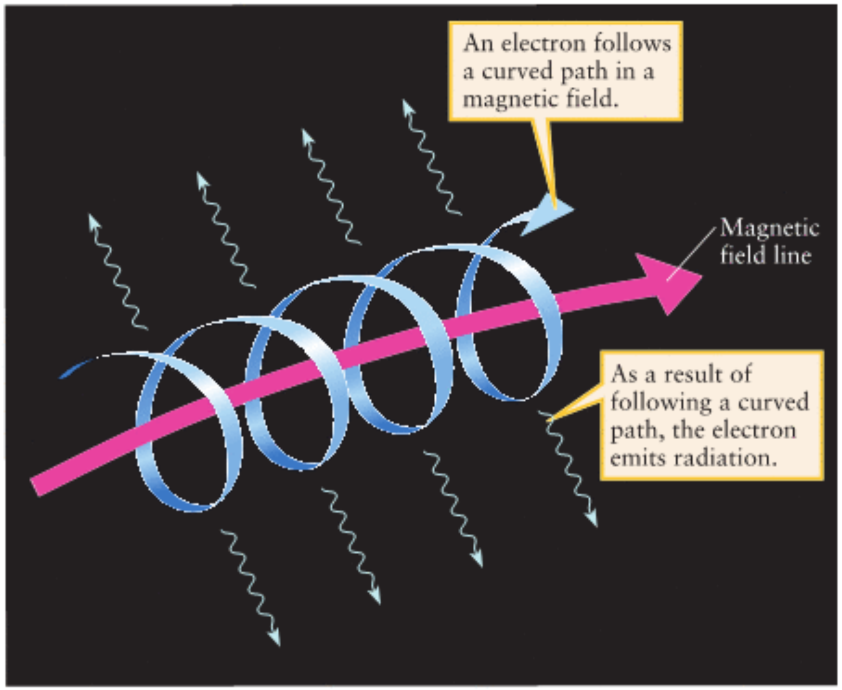
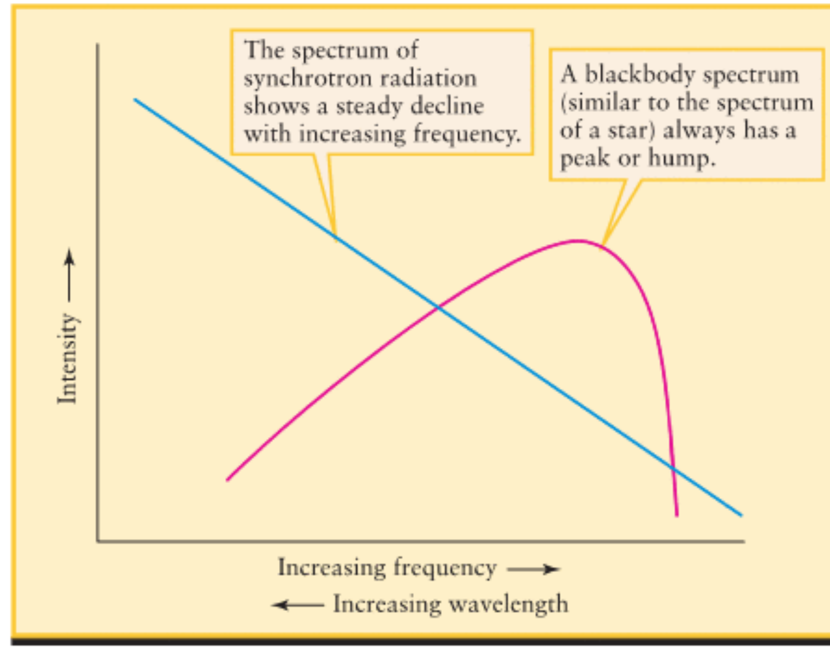
The **gamma-rays produce electrons and positrons** (pair production) that get accelerated and in turn emit their own gamma-rays, which create more electron-positron pairs, and so on. This **cascade creates a continuous synchrotron spectrum** including radio waves that get beamed along the magnetic axis direction. **When this beam of radio waves crosses the direction towards Earth we detect the beamed emission from the pulsar.**

Neutron Stars



(a)



(b)

The neutron star uses some of its rotational energy to accelerate electrons. These electrons radiate as they spiral around magnetic fields lines. This transfer of energy gradually slows down the neutron star.

How Do Neutron Stars Lose Energy?

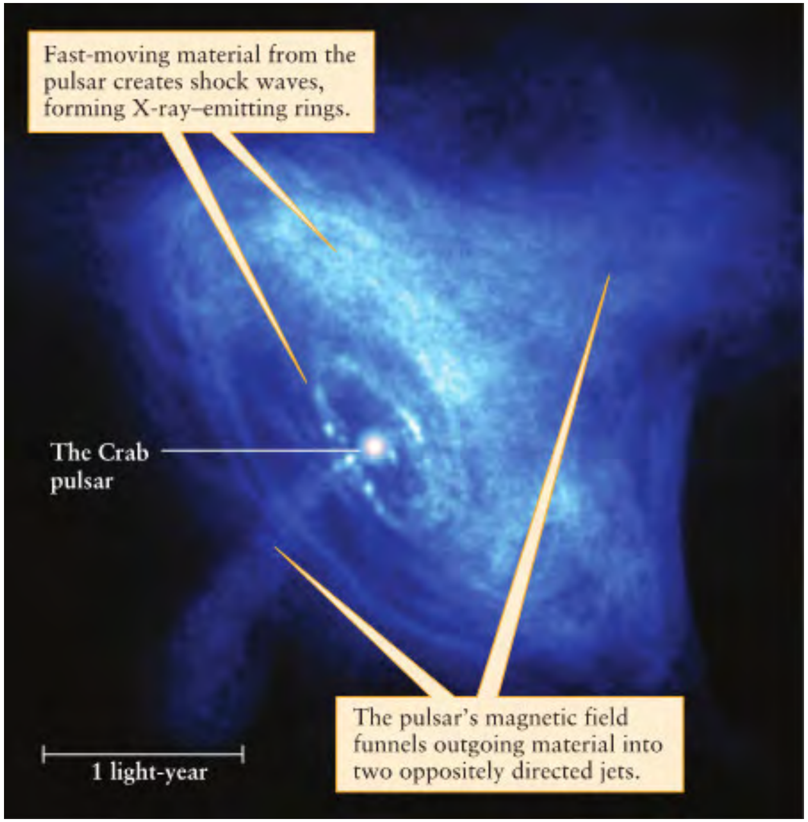
The energy source of a pulsar is kinetic energy of the spinning neutron star. Energy losses that result in the slowing down of a pulsar are:

1) The **pulsar radiates magnetic radiation** as the magnetic dipole rotates about the rotational axis.

2) Production of a **pulsar wind** from accelerated electrons that reach the light cylinder.

3) **Synchrotron emission** emitted by electrical charges accelerated in the magnetic field of the neutron star.

An isolated pulsar slows down as it ages, so its pulse period increases.



X-ray image of the Crab pulsar.

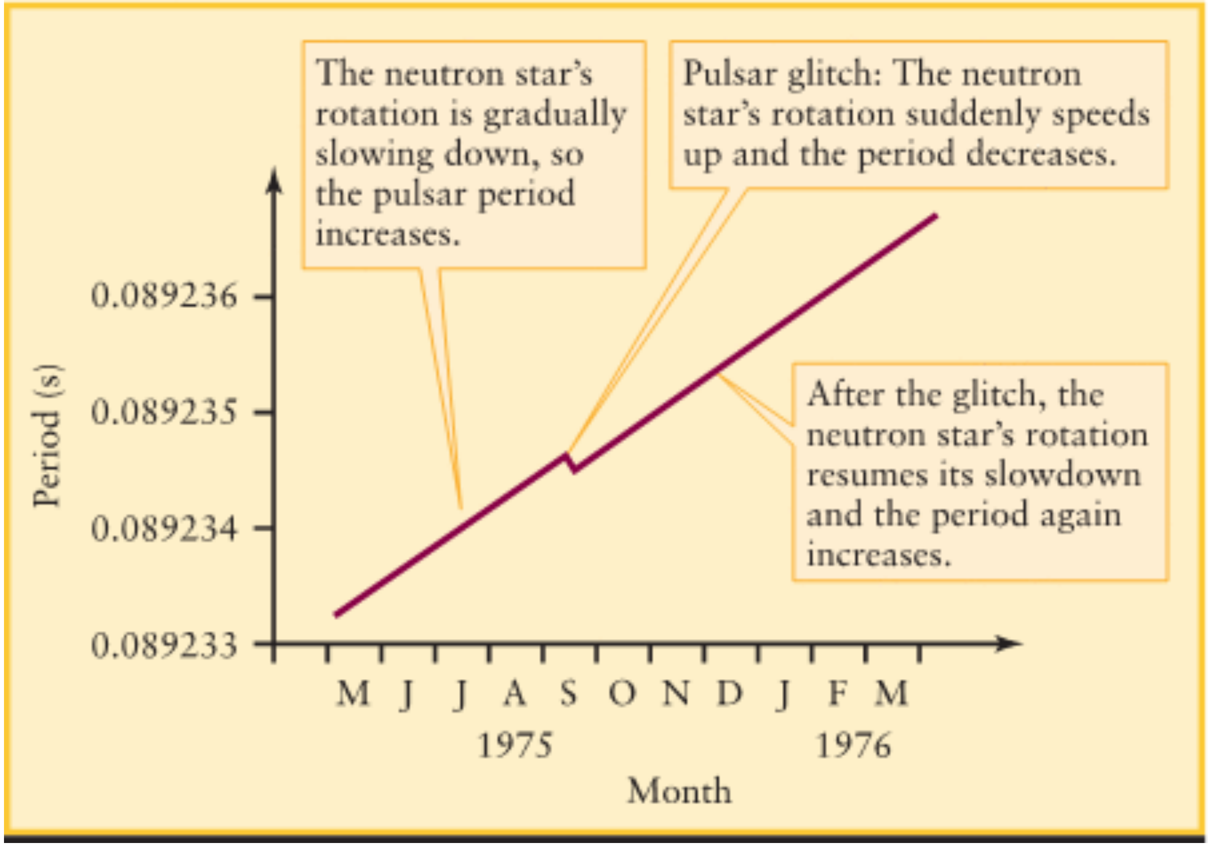
Interior of Neutron Star

A neutron star has a **solid crust on its surface** and an interior sea of degenerate neutrons. The crust is made mostly of Fe, with some nickel, germanium and krypton.

As one goes into the neutron star more free neutrons are present. These free **neutrons move around with no friction (superfluid).**

Friction-free **whirlpools of superfluid neutrons** may form in the interior. The interaction of these whirlpools with the crust maybe the cause of the observed sudden changes in the pulsar's rotation.

Pulsar Glitch

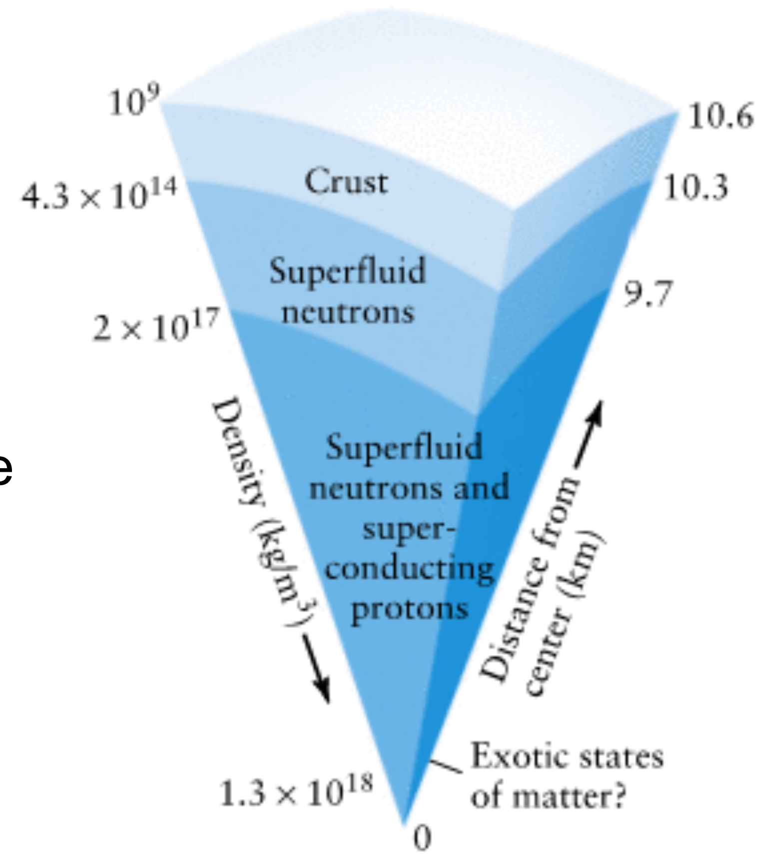


The rotational speed of a pulsar can suddenly increase. This is called a pulsar glitch. glitch.

Interior of Neutron Star

Models of the internal structure of a neutron star strongly suggest that the **protons in the core experience no electrical resistance** moving around. This phenomenon, is called **superconductivity**.

It has been speculated that near the core the pressure reaches a few $\times 10^{18}$ kg/m^3 at which levels the neutrons and protons dissolve into more fundamental particles called **quarks**.

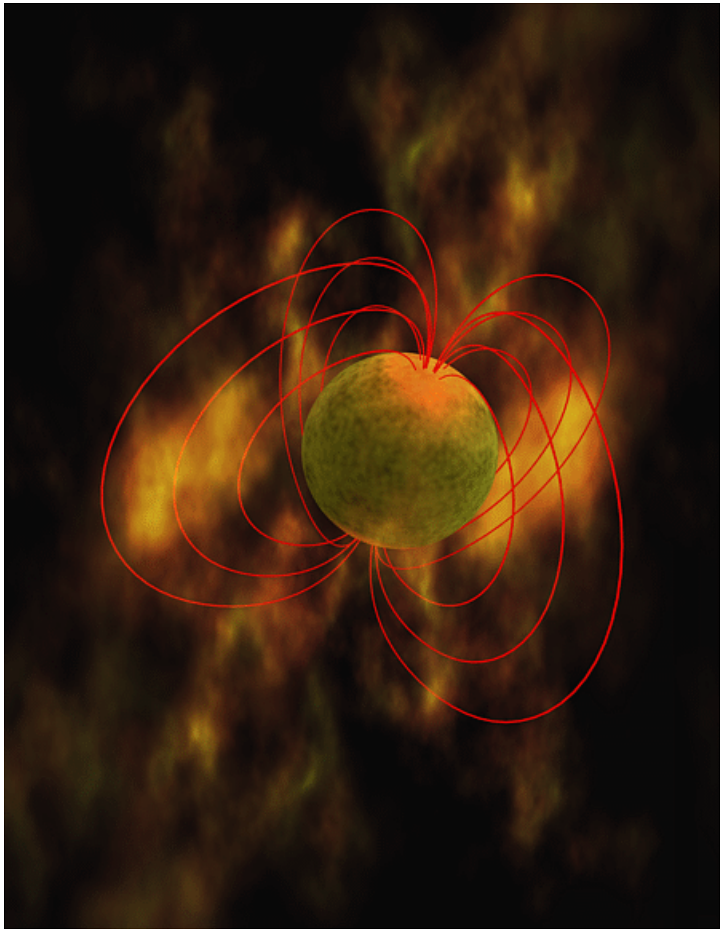


A model of a neutron star.

Magnetars

As a supergiant collapses to form a neutron star its magnetic field moves along with the infalling material and increases significantly up to values of 10^{12} Gauss.

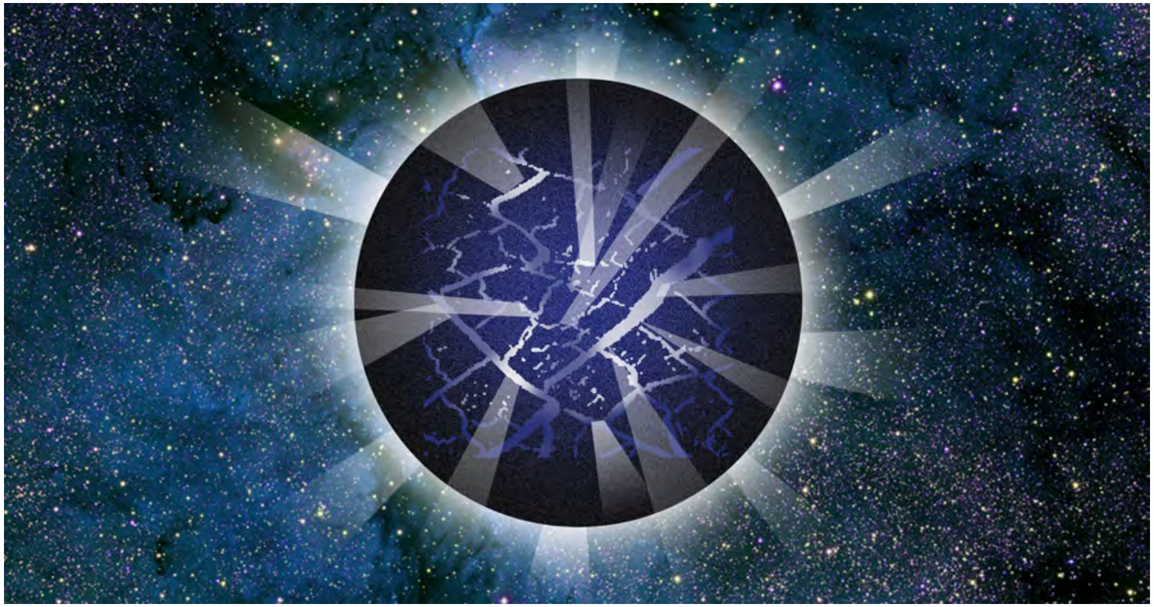
If during the collapse the neutron star is spinning fast enough that the rotation time is much less than the time for a convection cell to rise and fall then the magnetic field can reach 10^{15} G.
These **highly magnetized neutron stars are called magnetars**.



Starquakes

The **strong magnetic field** of a magnetar can **exert stresses** on the star's surface that can lead to fractures called **starquakes**.

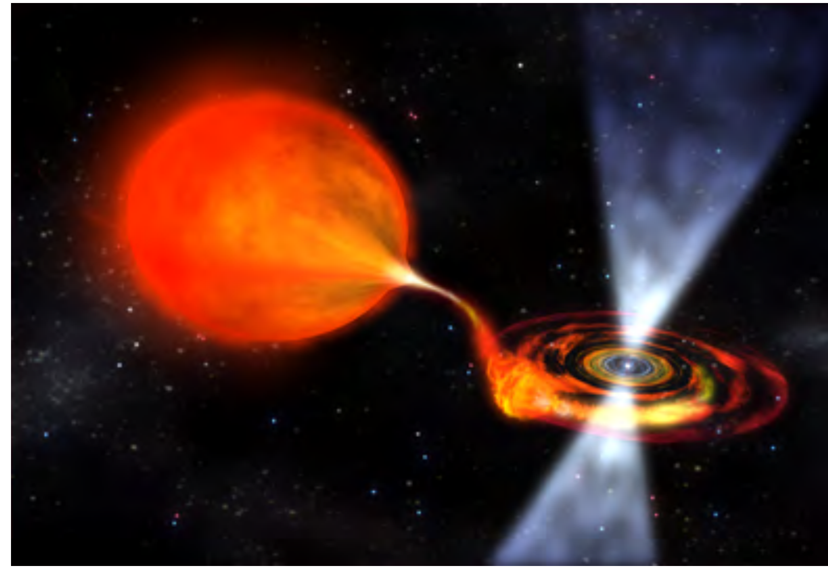
A starquake results in the rearrangement of the magnetic field and the reconnection of magnetic field lines. This reconnection results in a burst of gamma rays.



Millisecond Pulsars

Pulsars should slow down with age due to loss of kinetic energy.
So at first one might think that millisecond pulsars are young. But a young pulsar should be slowing down very quickly.

It turns out that PSR 1937+21 is slowing down very gradually which is characteristic of a pulsar that is hundreds of millions of years old.



In 1982 astronomers discovered millisecond pulsar PSR1937+21 (P =1.558 ms).

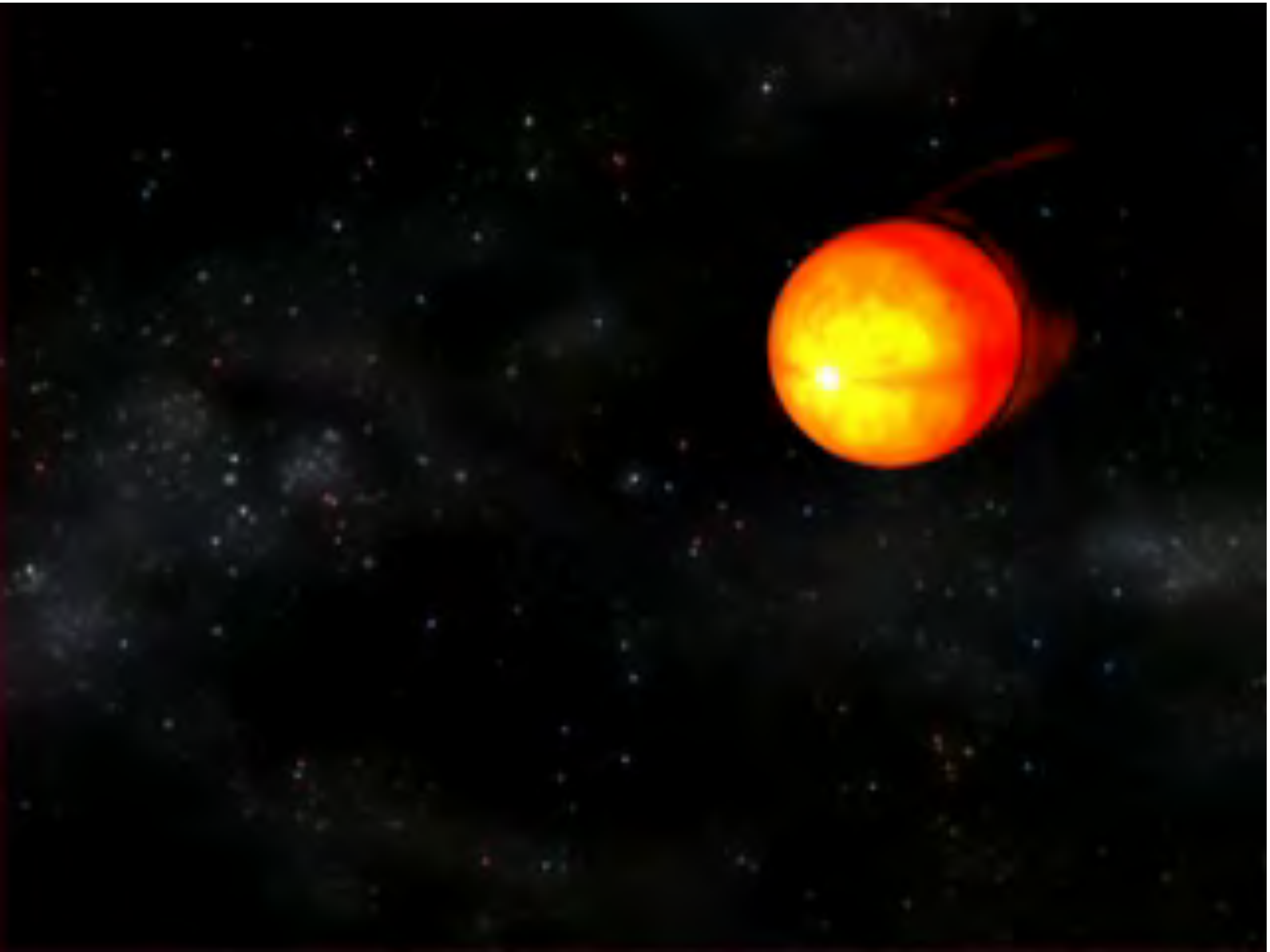
Explanation: Observations indicate that millisecond pulsars have been spun-up in binary systems!

Origin of Millisecond Pulsars

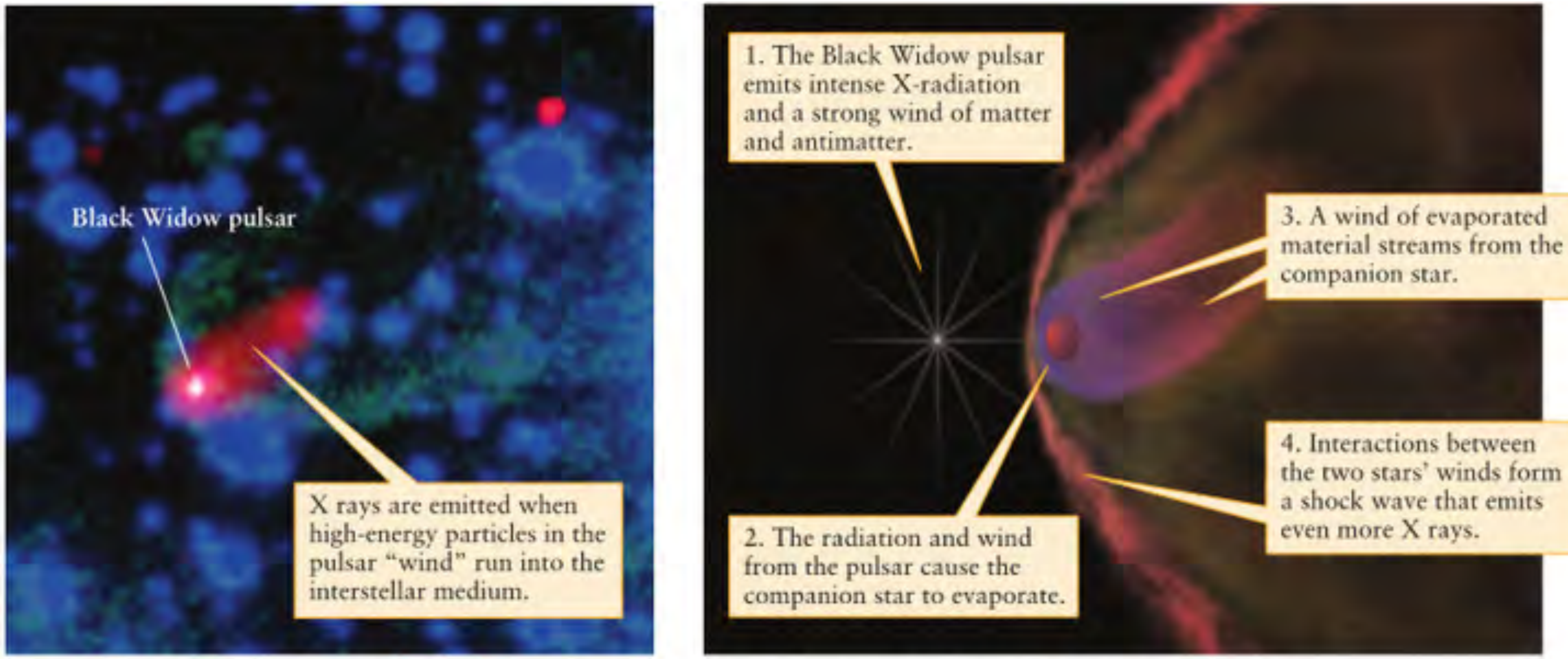
Consider a binary system consisting of a high-mass star and a low-mass star. The high-mass star will evolve faster and in a few million year becomes a Type II supernova forming a neutron star.

Over the next billion years the low mass star will evolve to become a red giant filling its Roche lobe and transferring material to the neutron star.

The infalling gas strikes the neutron star’s surface at high speed and at an angle that causes the star to spin faster. In this way, a slow, aging pulsar is “spun up” by mass transfer from its bloated companion.



Black Widow Pulsar



(a) The Black Widow pulsar R I V U X G (b) An illustration of the pulsar and its companion

A solitary millisecond pulsar is thought to have been part of close binary system, but the companion star was eroded away by the high-energy particles emitted by the pulsar after it was spun up. The Black Widow pulsar may be caught in the act of destroying its companion in just such a process.

Thought Question

Could there be neutron stars that appear as pulsars to other civilizations but not to us?

A. Yes
B. No

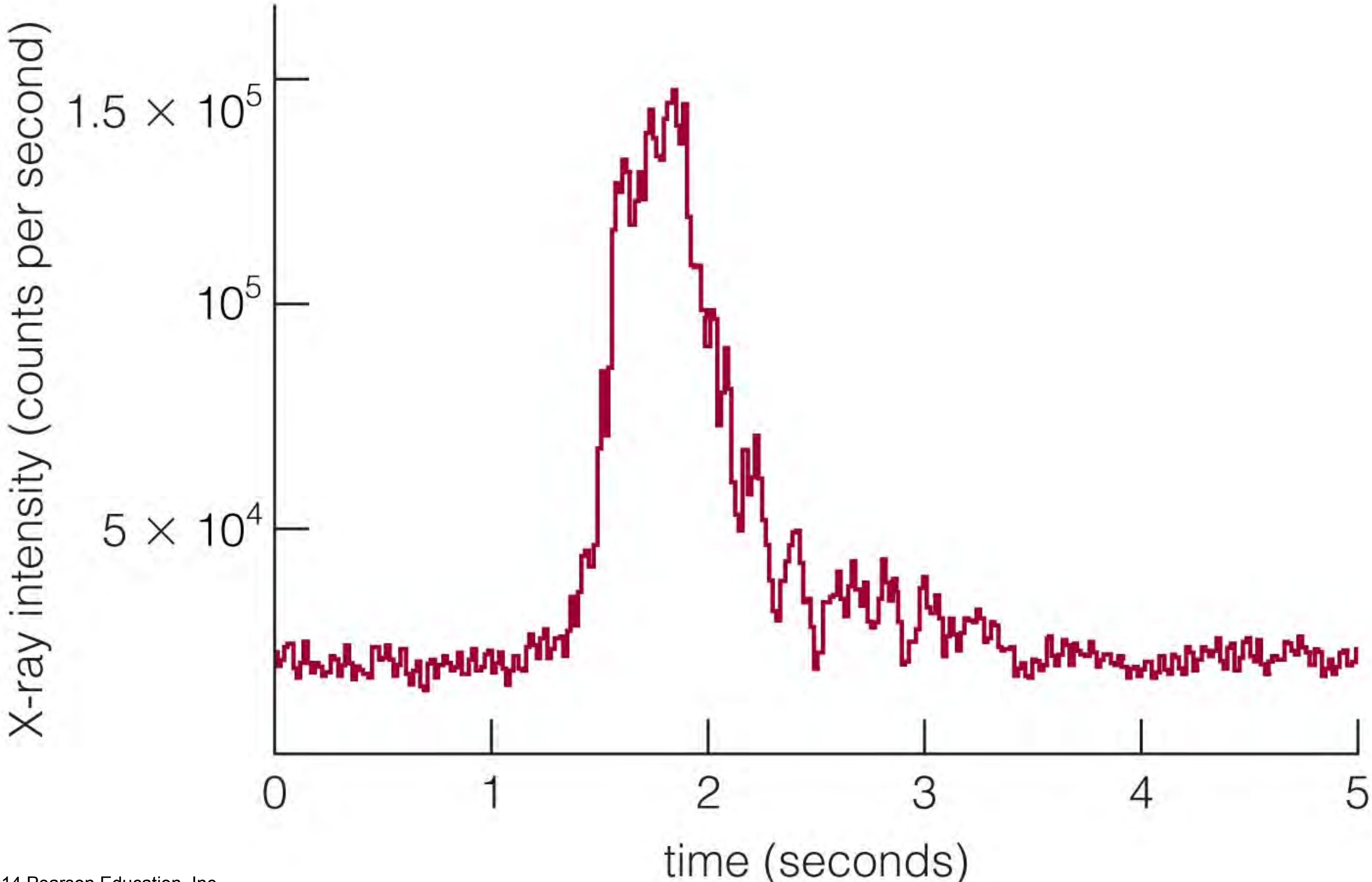
Thought Question

Could there be neutron stars that appear as pulsars to other civilizations but not to us?

A. Yes

B. No

What can happen to a neutron star in a close binary system?



Thought Question

According to the conservation of angular momentum, what would happen if a star orbiting in a direction <u>opposite</u> the neutron's star rotation fell onto a neutron star?

A. The neutron star's rotation would speed up.
B. The neutron star's rotation would slow down.
C. Nothing. The directions would cancel each other out.

Thought Question

According to the conservation of angular momentum, what would happen if a star orbiting in a direction <u>opposite</u> the neutron's star rotation fell onto a neutron star?

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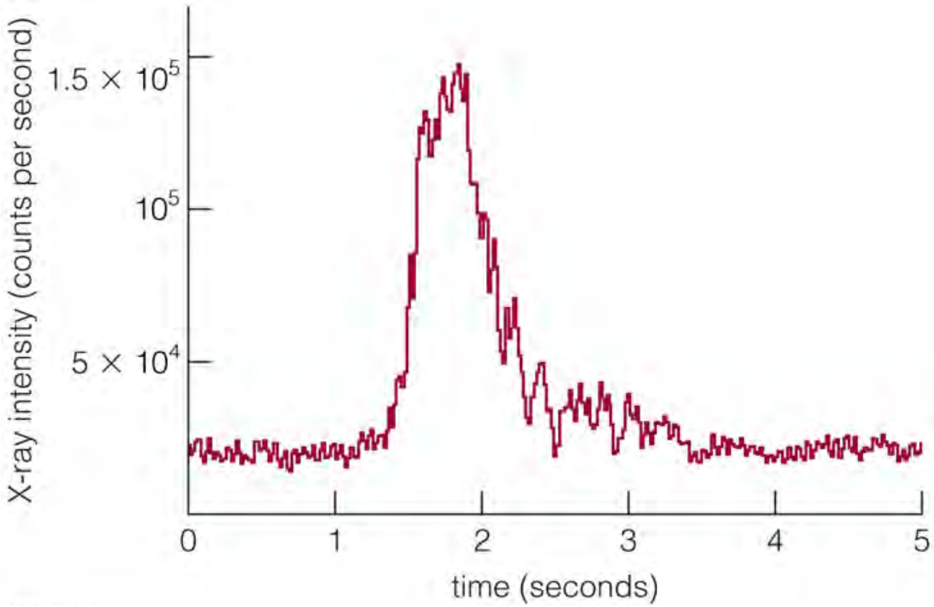
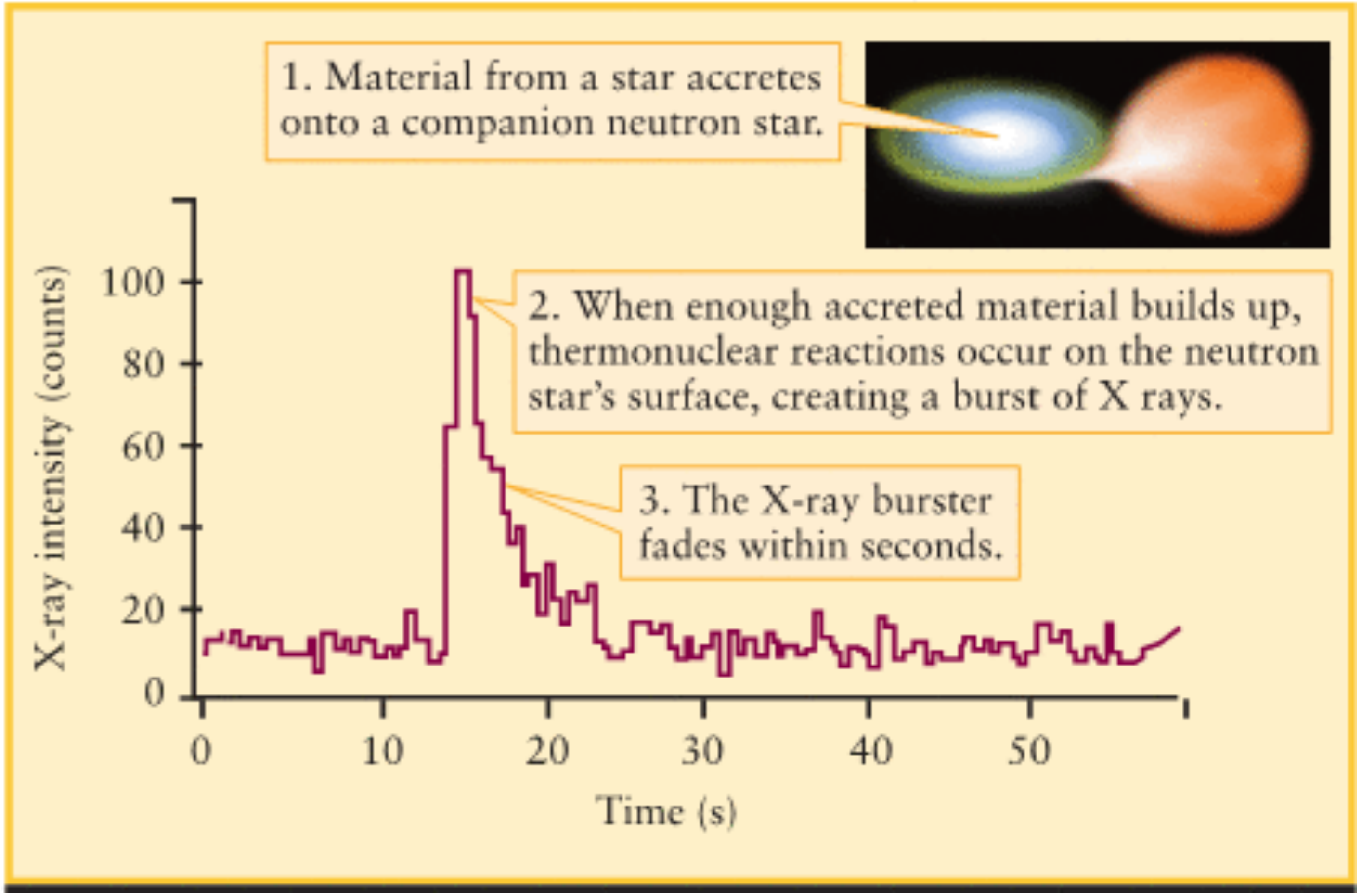
X-Ray Bursts



- Matter accreting onto a neutron star can eventually become hot enough for helium fusion.
- The sudden onset of fusion produces a burst of X rays.

X-Ray Bursts



Whereas explosive hydrogen fusion on a white dwarf produces a nova, explosive helium fusion on a neutron star produces an X-ray burster.

What have we learned?

- **What is a neutron star?**
  – It is a ball of neutrons left over from a massive star supernova and supported by neutron degeneracy pressure.
- **How were neutron stars discovered?**
  – Beams of radiation from a rotating neutron star sweep through space like lighthouse beams, making them appear to pulse.
  – Observations of these pulses were the first evidence for neutron stars.

What have we learned?

- **What can happen to a neutron star in a close binary system?**
  - The accretion disk around a neutron star can become hot enough to produce X rays, making the system an X-ray binary.
  - Sudden fusion events periodically occur on a the surface of an accreting neutron star, producing X-ray bursts.

18.3 Black Holes: Gravity's Ultimate Victory

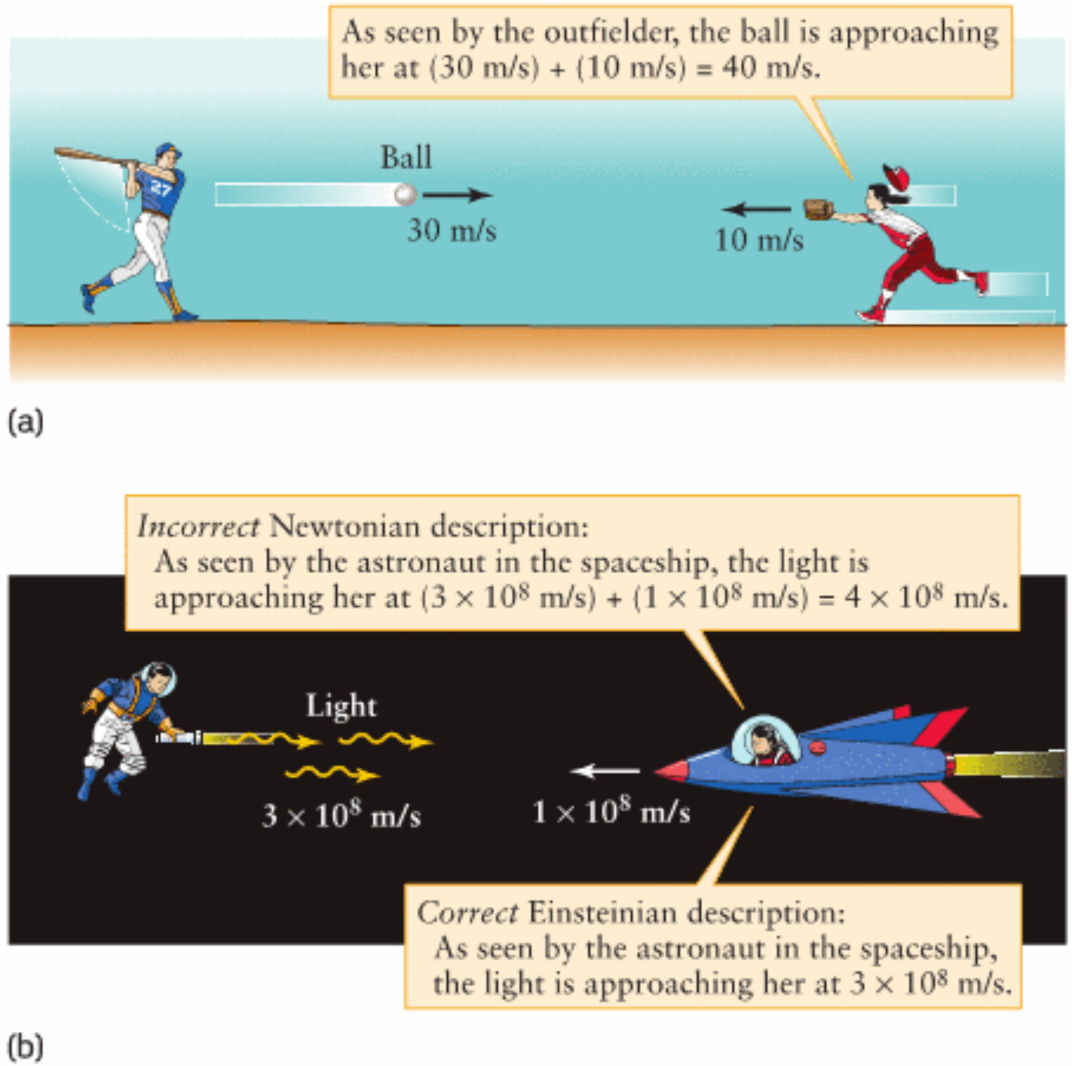
- Our goals for learning:
  - **Special and general relativity**
  - **What is a black hole?**
  - **What would it be like to visit a black hole?**
  - **Do black holes really exist?**

Special Relativity

Principles of Special Relativity:
1. The laws of physics are the same for all inertial observers.

2. The speed of light is the same for all **inertial observers** regardless of the state of motion of the source.

An inertial observer is one that is not accelerating.


As seen by the outfielder, the ball is approaching her at (30 m/s) + (10 m/s) = 40 m/s.
Ball
30 m/s
10 m/s
(a)
Incorrect Newtonian description:
As seen by the astronaut in the spaceship, the light is approaching her at (3 × 10⁸ m/s) + (1 × 10⁸ m/s) = 4 × 10⁸ m/s.
Light
3 × 10⁸ m/s
1 × 10⁸ m/s
Correct Einsteinian description:
As seen by the astronaut in the spaceship, the light is approaching her at 3 × 10⁸ m/s.
(b)

Special Relativity

The length you measure an object to have depends on how that object is moving; the faster it moves, the shorter its length along its direction of motion. This phenomenon is called **length contraction.**

$$L = L_0\sqrt{1-\left(\frac{v}{c}\right)^2}$$

L = observed length of object along direction of motion

L_0 = length of object at rest (proper length)

v = speed of object with respect to observer

c = speed of light

Special Relativity

A clock runs slower when observed by someone moving relative to the clock than someone not moving relative to the clock. This phenomenon is called time dilation.

$$T = \frac{T_0}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$$

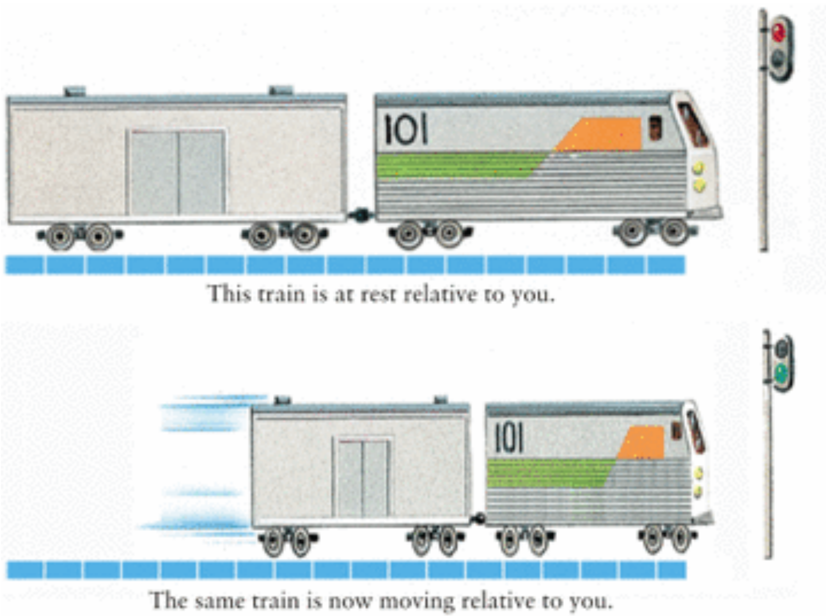
T = time interval measured by an observer moving relative to the phenomenon

T_0 = time interval measured by an observer not moving relative to the phenomenon

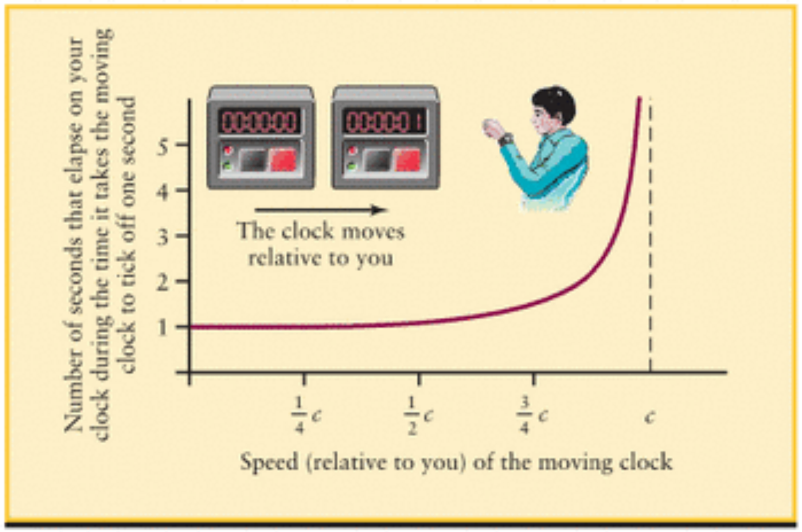
v = speed of phenomenon relative to observer

c = speed of light

Special Relativity



(a) Length contraction



(b) Time dilation

Special Relativity

Example 1: William is travelling in his spaceship at 98% of the speed of light relative to Alex. If William holds a 1 m ruler parallel to the direction of motion, how long is this ruler as measured by Alex?

Special Relativity

Special relativity also predicts the famous relationship:

$$E = mc^2$$

In fusion reactions mass is converted to energy and this released energy is what powers the stars.

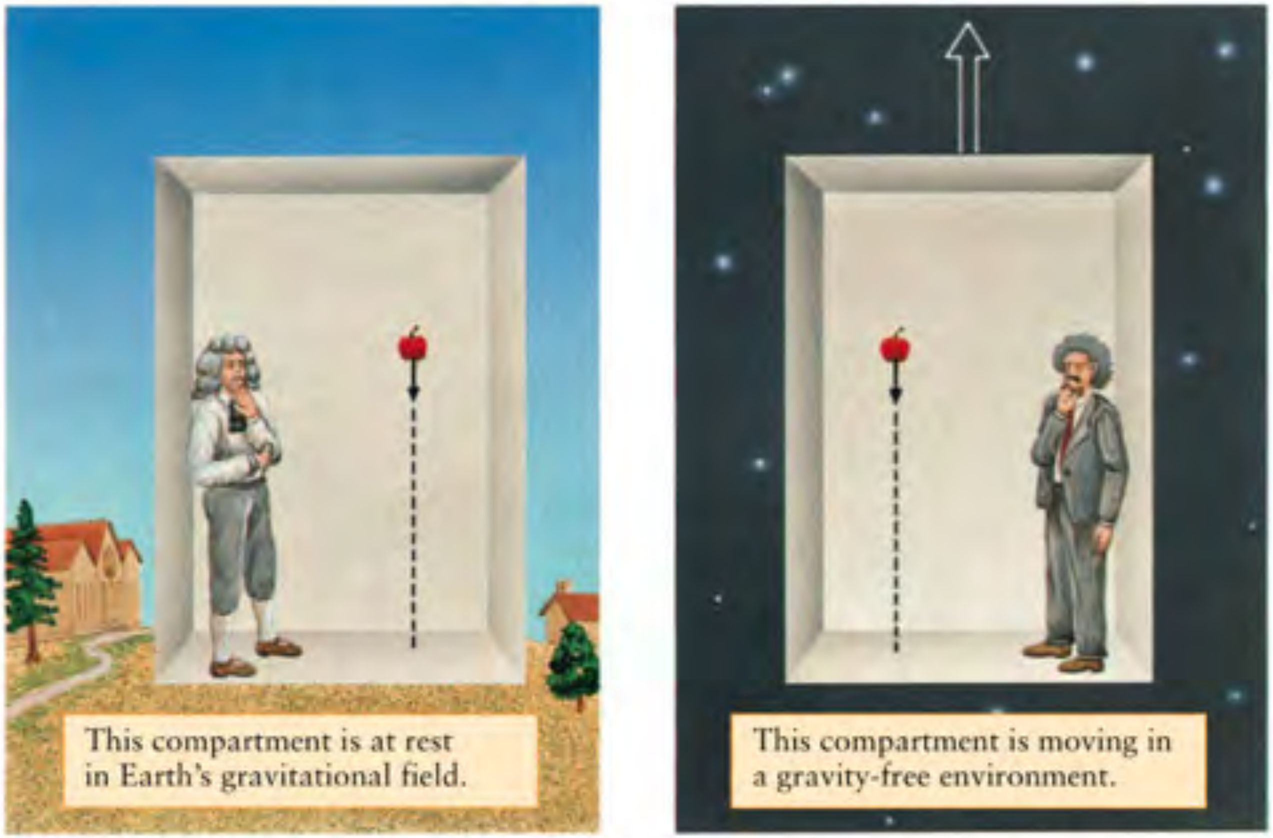
General Theory of Relativity

The **equivalence principle** asserts that you cannot distinguish between :

(a) being at rest in a gravitational field and

(b) being accelerated upward in a gravity-free environment. This idea was an important step in Einstein's quest to develop the general theory of relativity.

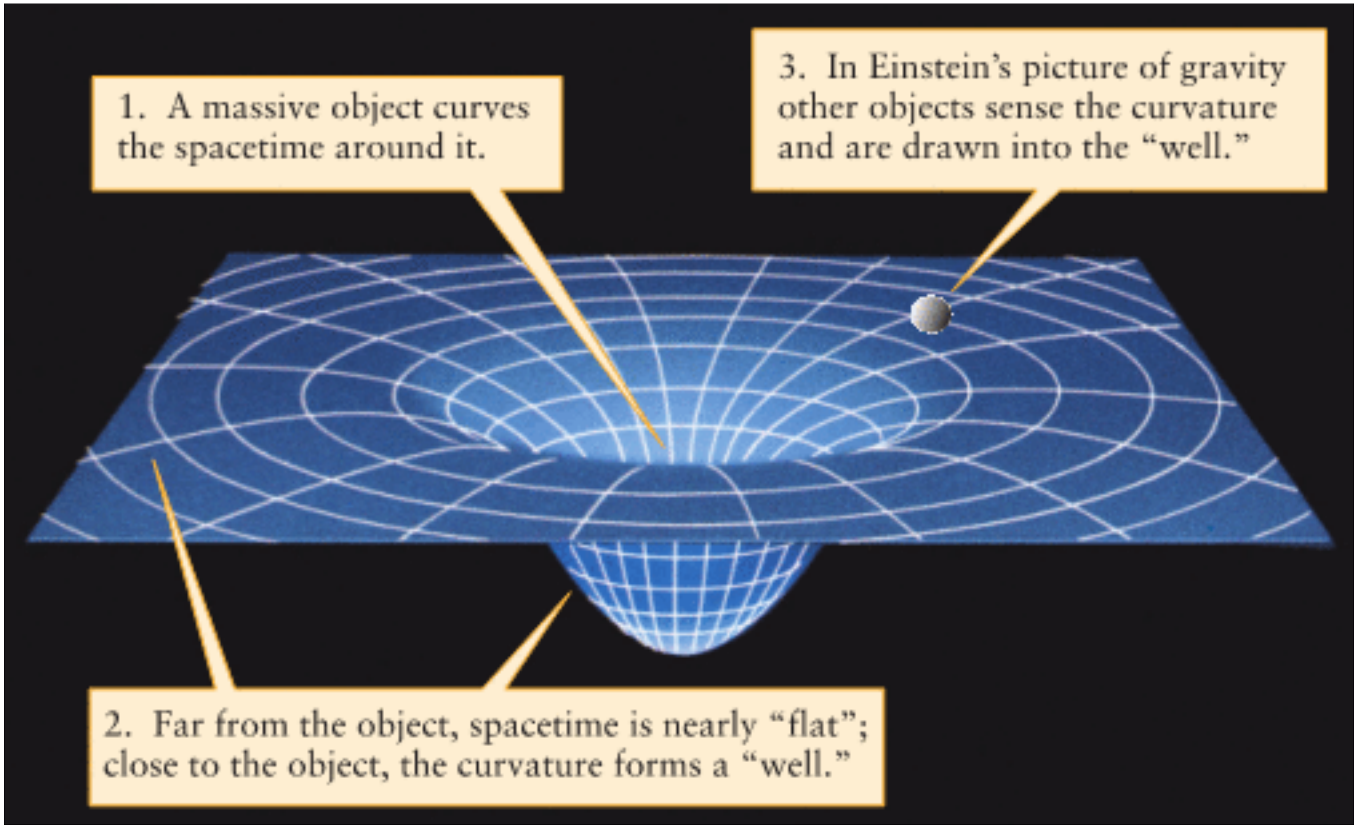
General Theory of Relativity



(a) The apple hits the floor of the compartment because Earth's gravity accelerates the apple downward.

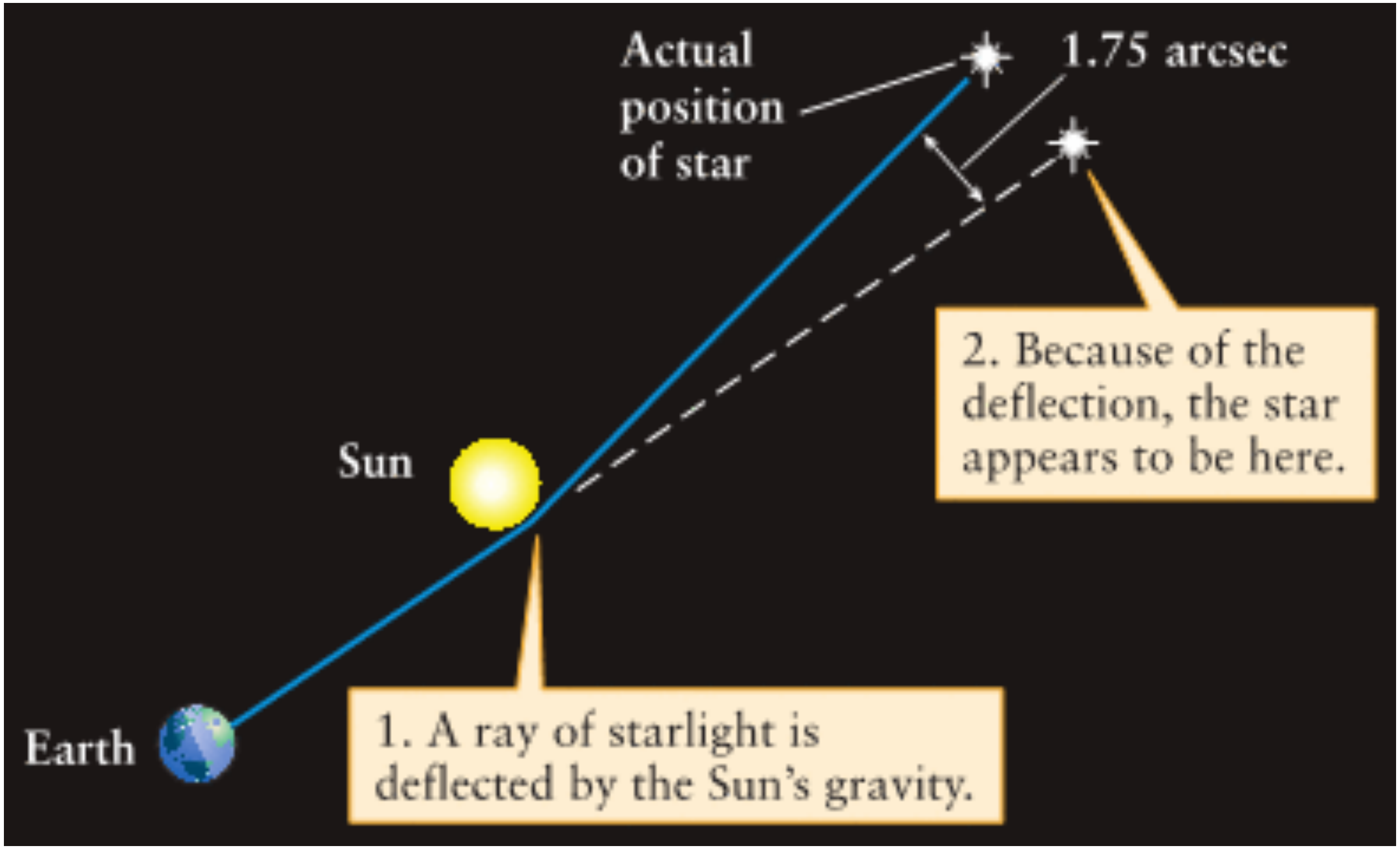
(b) The apple hits the floor of the compartment because the compartment accelerates upward.

General Theory of Relativity

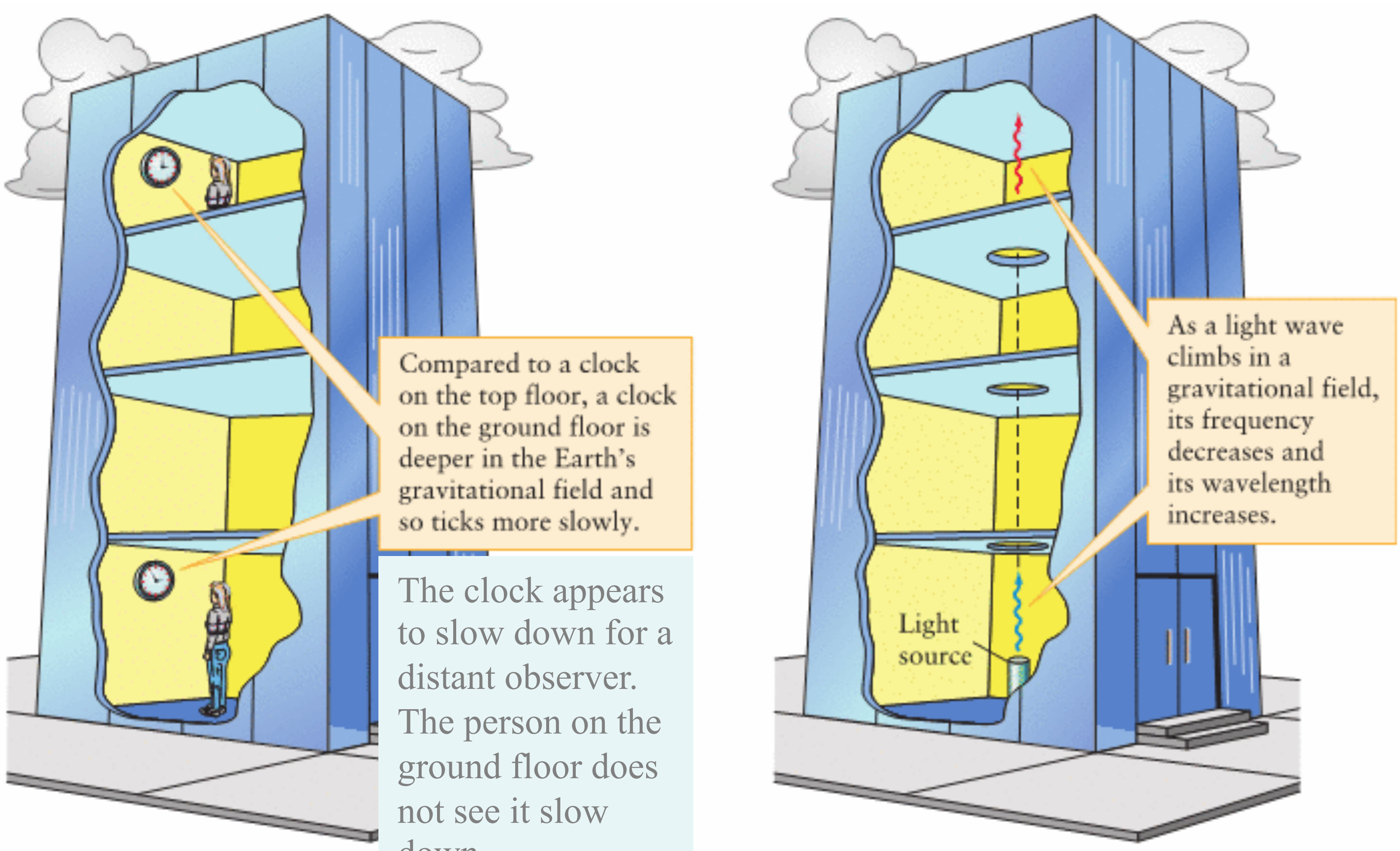


Einstein envisioned gravity as being caused by curvature of space. Above is a two dimensional analogy to help understand the curvature of four-dimensional spacetime.

Testing the General Theory of Relativity



Gravitational Slowing of Time and Gravitational Redshift

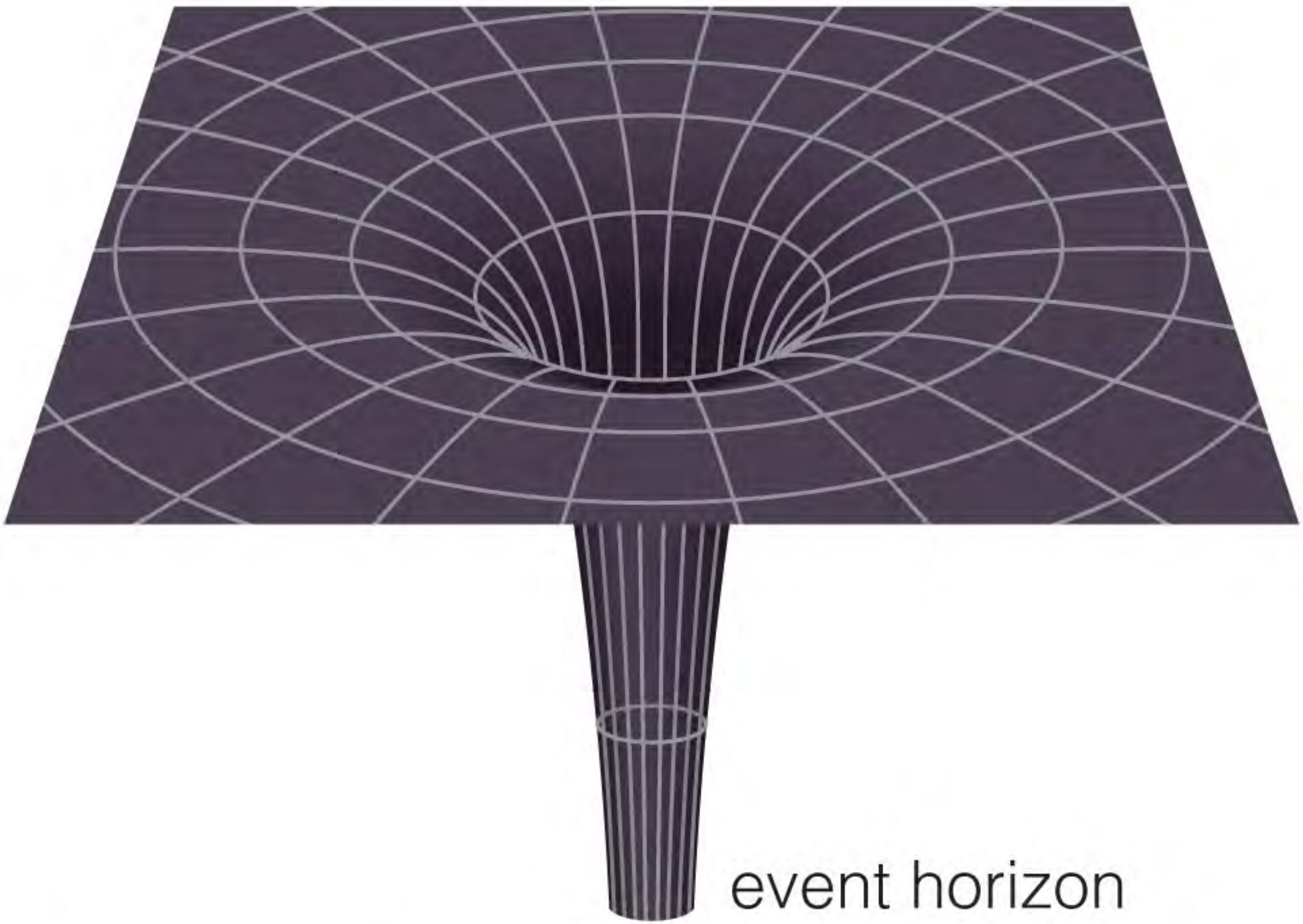


The clock appears to slow down for a distant observer. The person on the ground floor does not see it slow down.

(a) The gravitational slowing

(b) The gravitational redshift

What is a black hole?



- A ***black hole*** is an object whose gravity is so powerful that not even light can escape it.

Thought Question

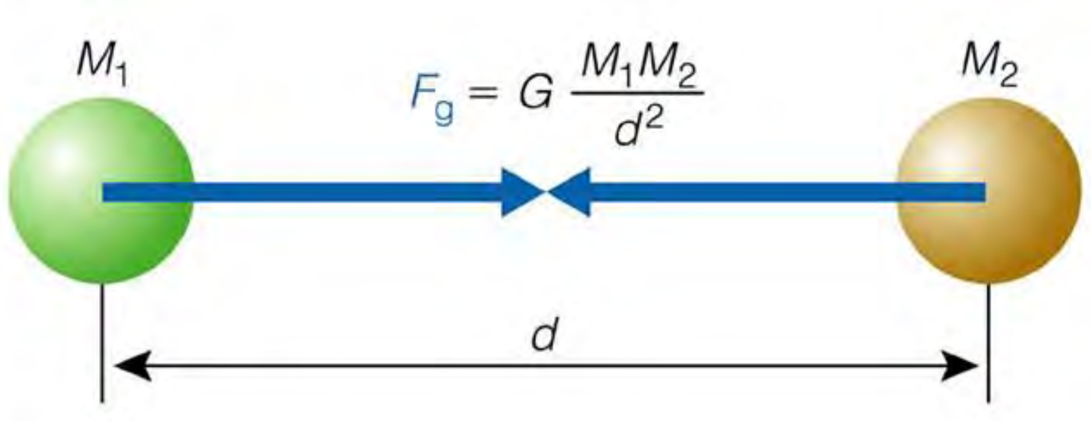
What happens to the escape velocity from an object if you shrink it?

A. It increases.

B. It decreases.

C. It stays the same.

Hint:

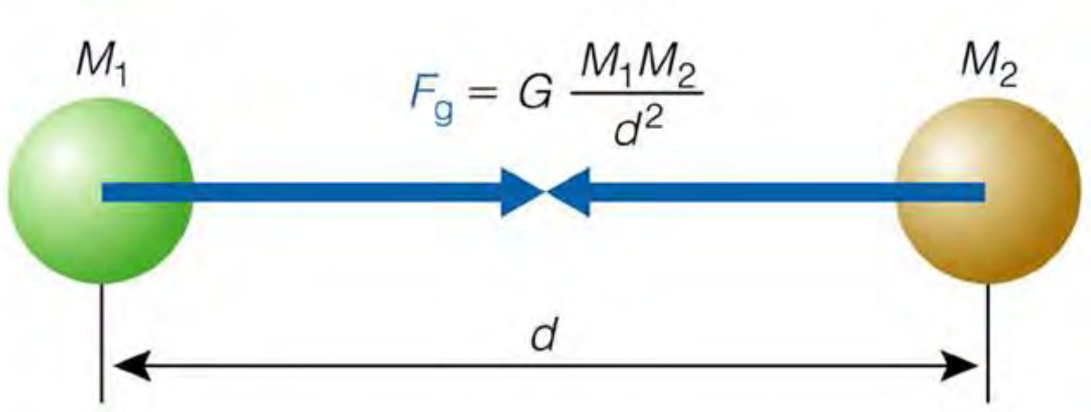


Thought Question

What happens to the escape velocity from an object if you shrink it?

A. **It increases.**
B. It decreases.
C. It stays the same.

Hint:



Escape Velocity

$$E_{total} = \text{Kinetic Energy} + \text{Potential Energy} = E_K + E_P$$

$$\text{Total Energy On Surface} = \text{Total Energy at Infinity}$$

$$E_{K,surface} + E_{P,surface} = E_{K,\infty} + E_{P,\infty} \Rightarrow$$

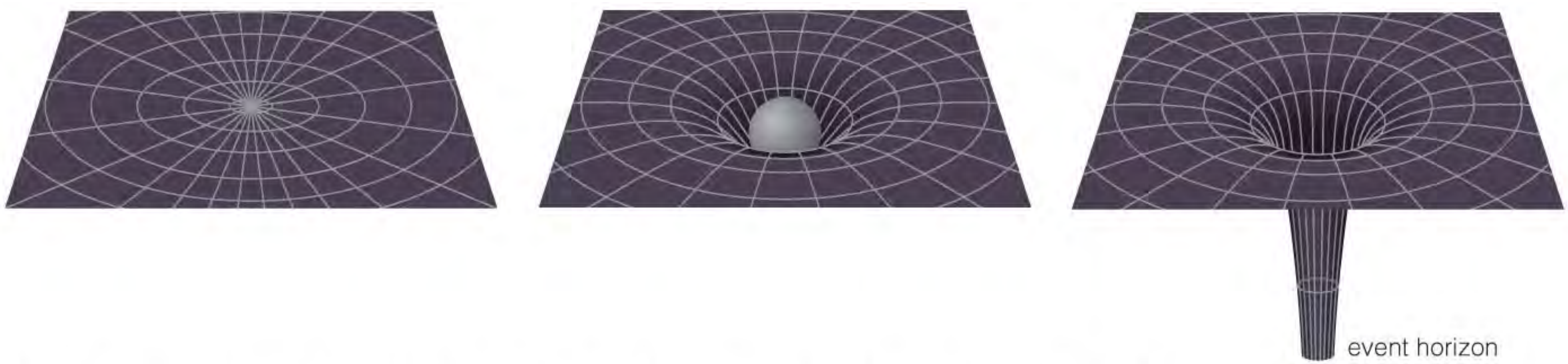
$$\frac{1}{2}mv_{Surface}^2 - \frac{GMm}{R} = \frac{1}{2}mv_{\infty}^2 - \frac{GMm}{\infty} \Rightarrow$$

$$\frac{1}{2}mv_{Surface}^2 = \frac{GMm}{R} \Rightarrow v_{Surface}^2 = \frac{2GM}{R}$$

"Surface" of a Black Hole

- The "surface" of a black hole is the radius at which the escape velocity equals the speed of light.
- This spherical surface is known as the ***event horizon.***
- The radius of the event horizon is known as the ***Schwarzschild radius.***

- A black hole's mass strongly warps space and time in the vicinity of its event horizon.



No Escape

- Nothing can escape from within the event horizon because nothing can go faster than light.
- No escape means there is no more contact with something that falls in. It increases the hole mass, changes the spin or charge, but otherwise loses its identity.

Neutron Star Limit

- Quantum mechanics says that neutrons in the same place cannot be in the same state.
- Neutron degeneracy pressure can no longer support a neutron star against gravity if its mass exceeds about $3M_{sun.}$
- Some massive star supernovae can make a black hole if enough mass falls onto core.

Singularity

- Beyond the neutron star limit, no known force can resist the crush of gravity.
- As far as we know, gravity crushes all the matter into a single point known as a ***singularity.***

Thought Question

How does the radius of the event horizon change when you add mass to a black hole?

A. It increases.
B. It decreases.
C. It stays the same.

Thought Question

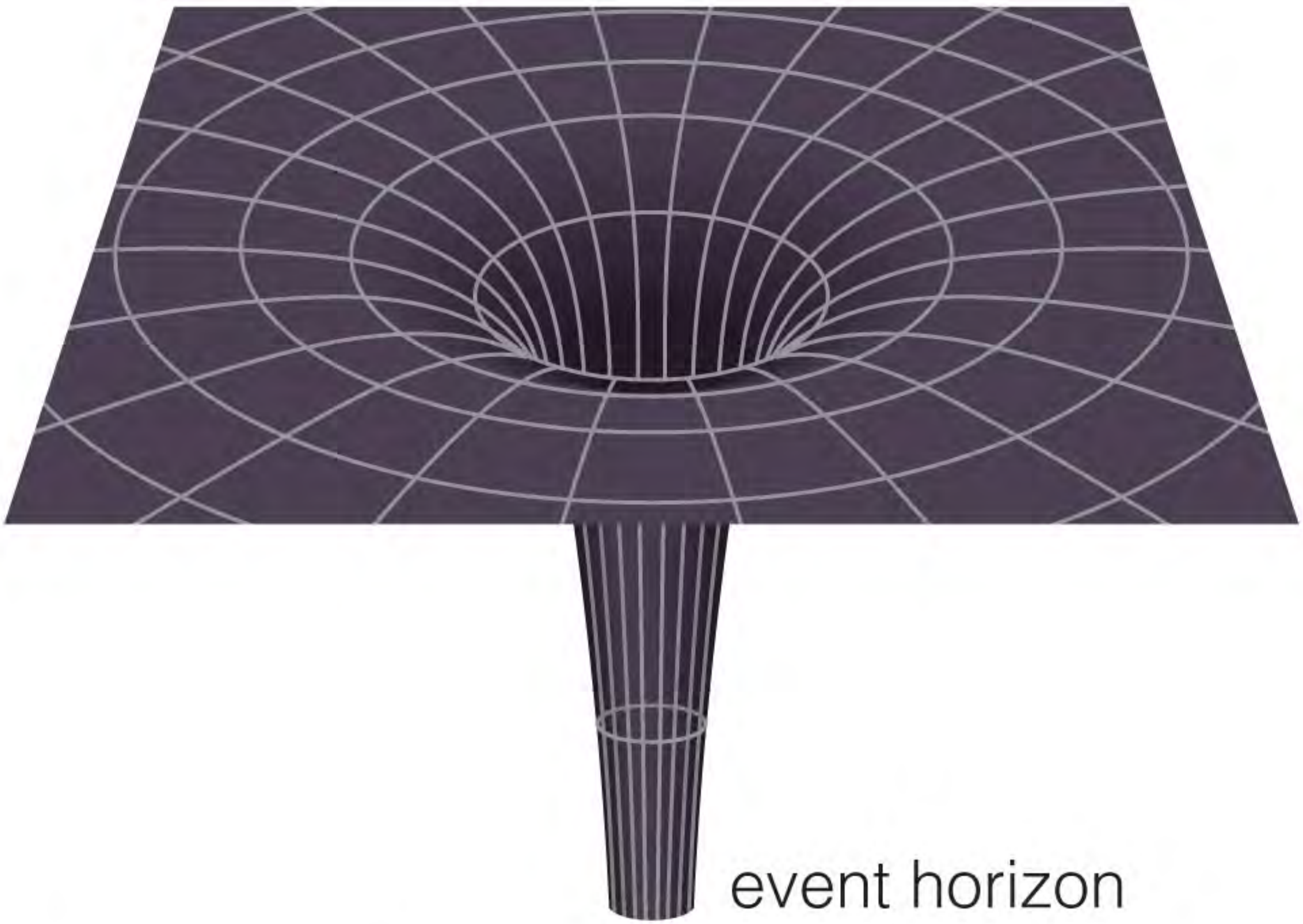
How does the radius of the event horizon change when you add mass to a black hole?

A. It increases.

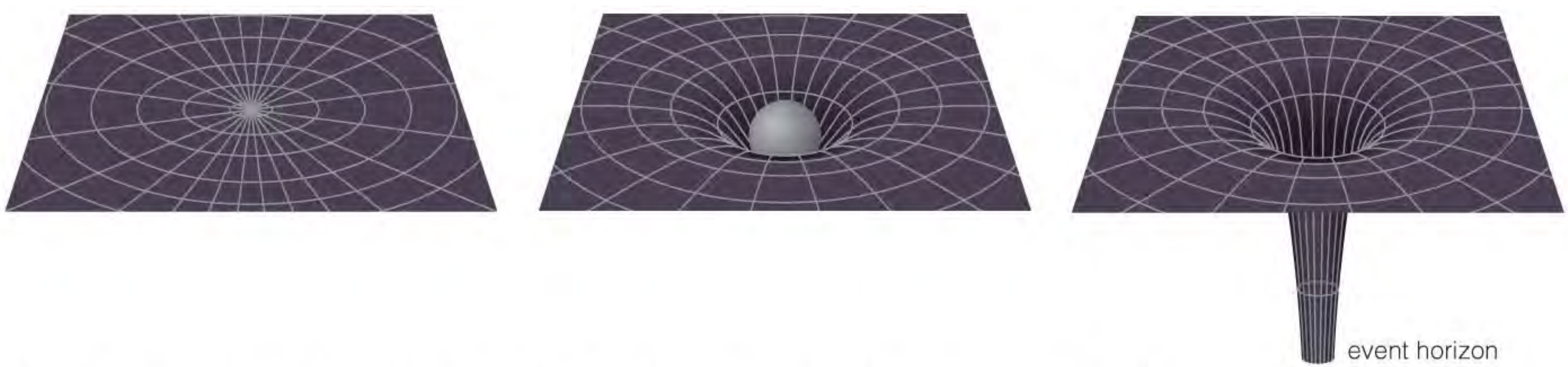
B. It decreases.

C. It stays the same.

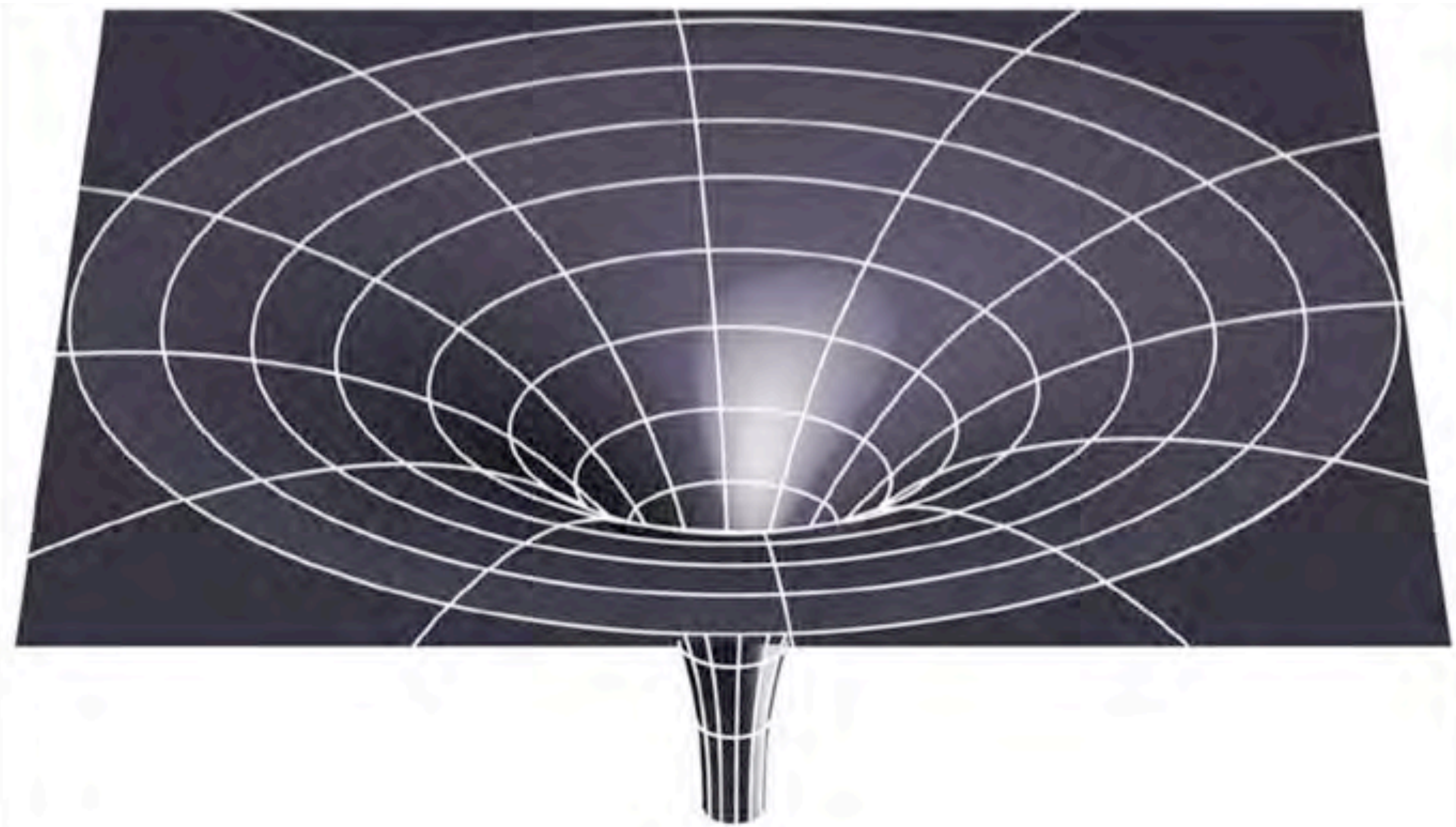
What would it be like to visit a black hole?



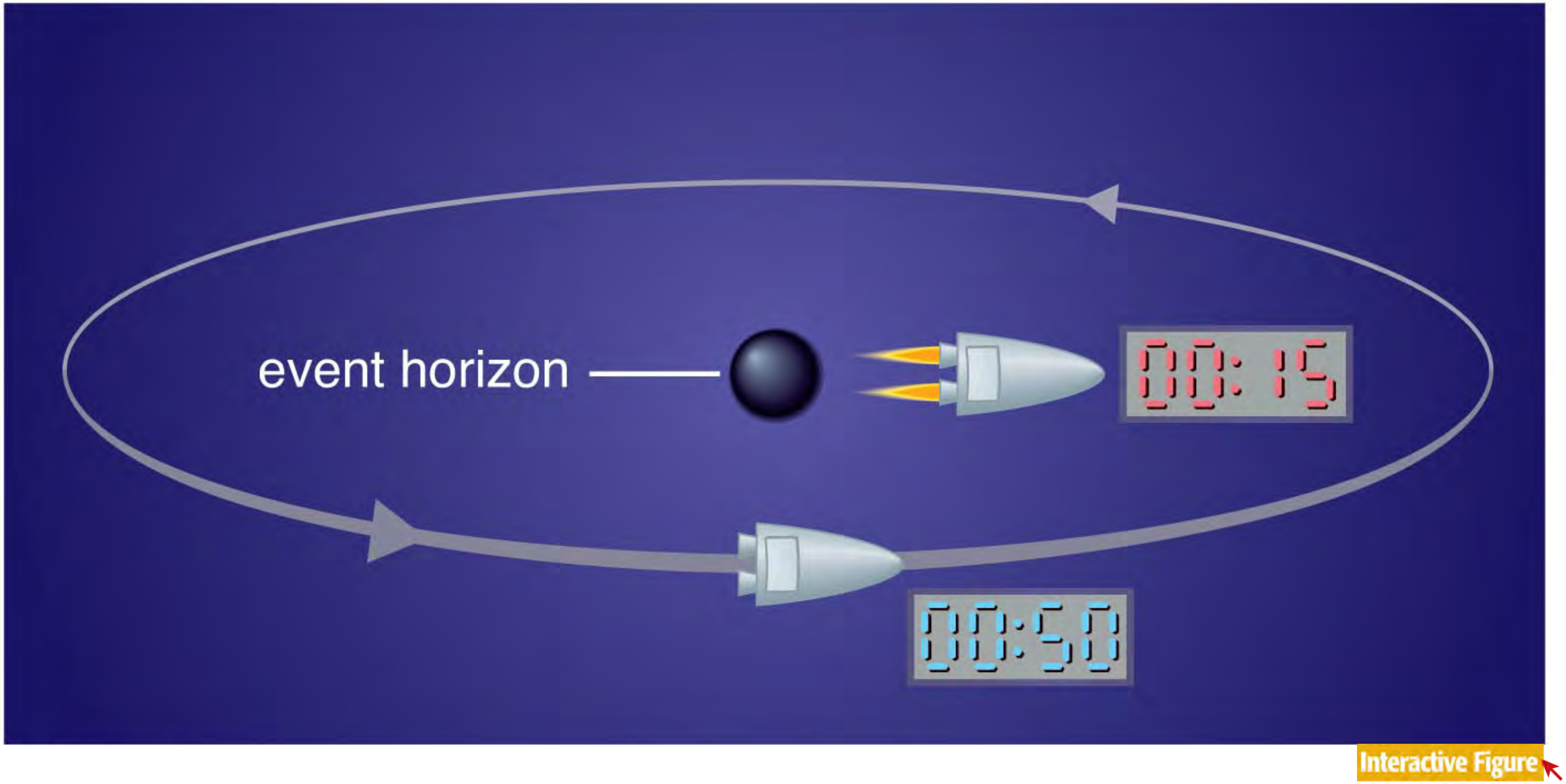
- If the Sun became a black hole, its gravity would be different only near the event horizon.



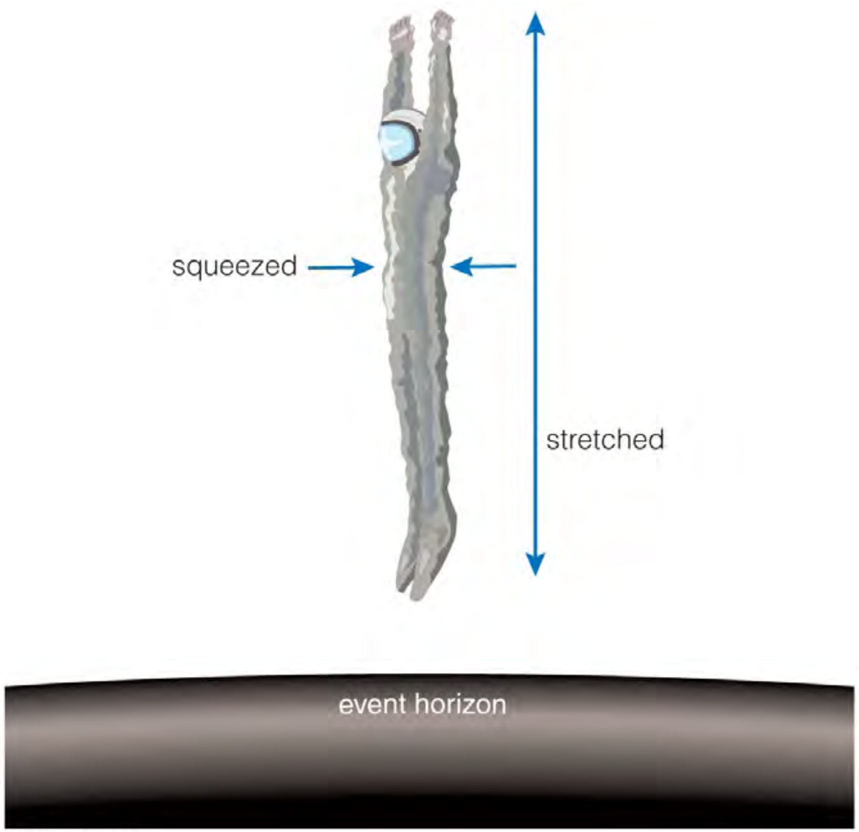
Black holes don't suck!



- Light waves take extra time to climb out of a deep hole in spacetime, leading to a ***gravitational redshift.***

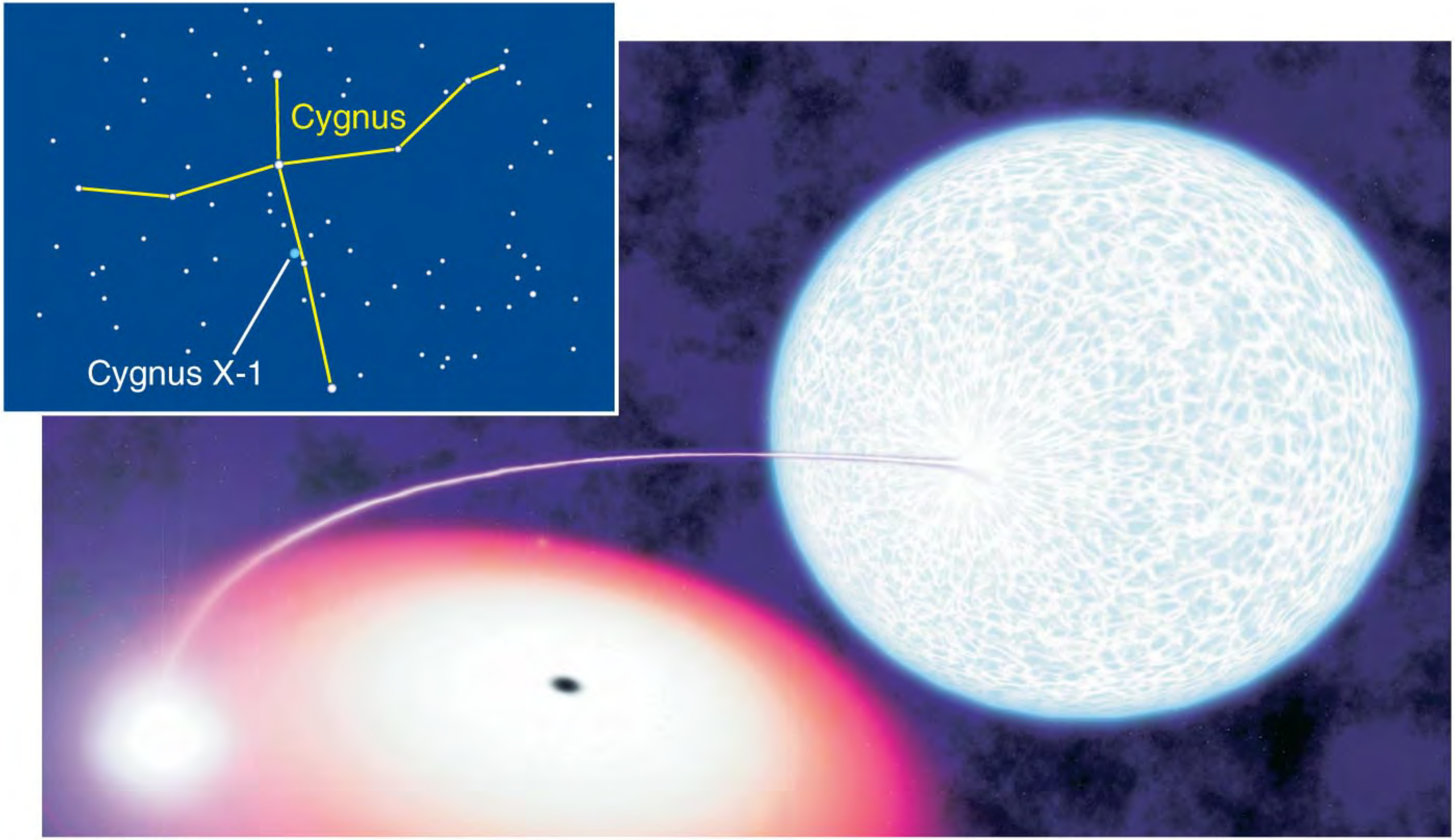


- Time passes more slowly near the event horizon.



- Tidal forces near the event horizon of a $3M_{\text{Sun}}$ black hole would be lethal to humans.
- Tidal forces would be gentler near a supermassive black hole because its radius is much bigger.

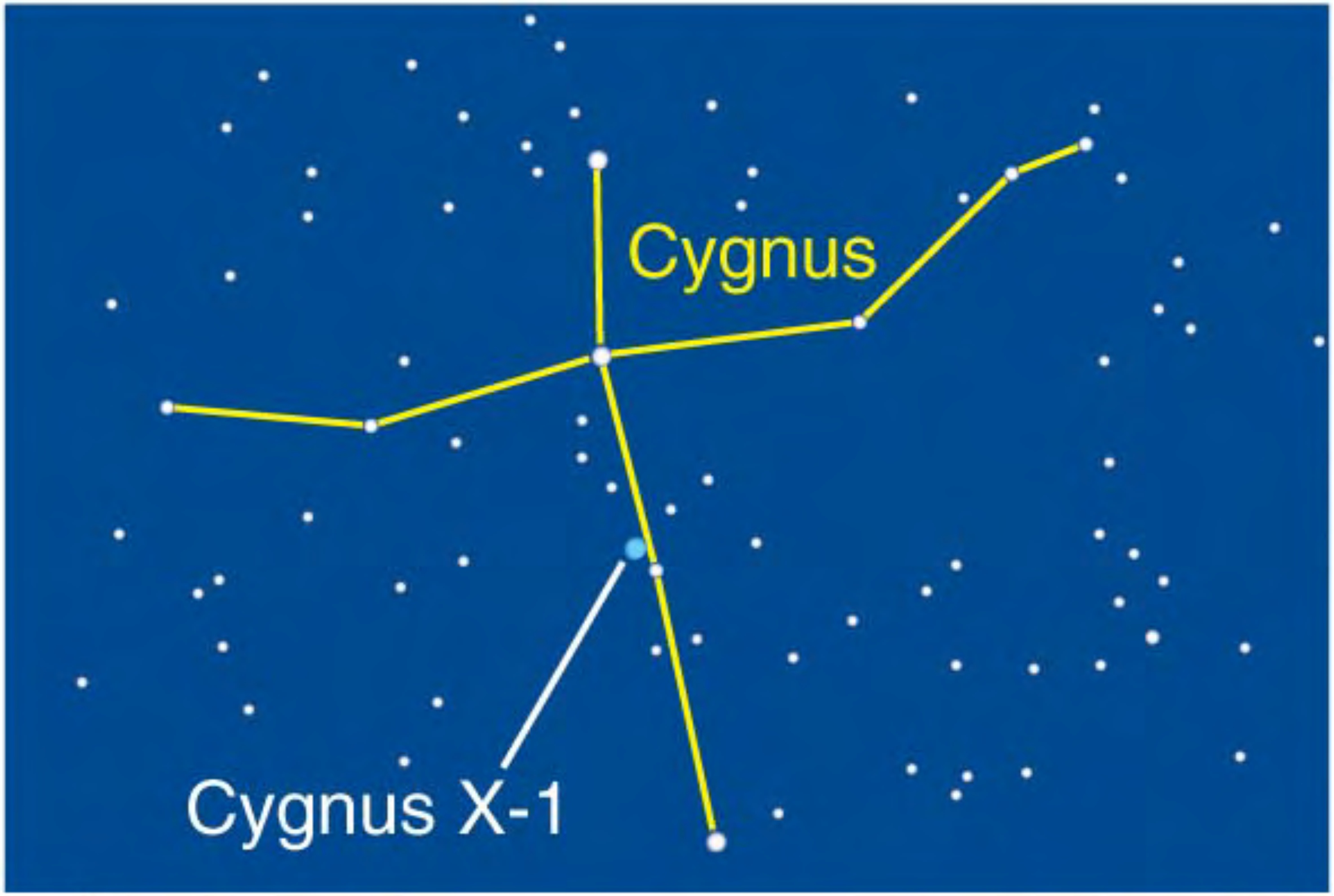
Do black holes really exist?



Black Hole Verification

- We need to measure mass by:
  - Using orbital properties of a companion
  - Measuring the velocity and distance of orbiting gas

- It's a black hole if it's not a star and its mass exceeds the neutron star limit (~$3M_{\text{Sun}}$)



- One famous X-ray binary with a likely black hole is in the constellation Cygnus.

Cygnus X-1

Cygnus X-1 is thought to be a black hole in a binary system with a companion supergiant.

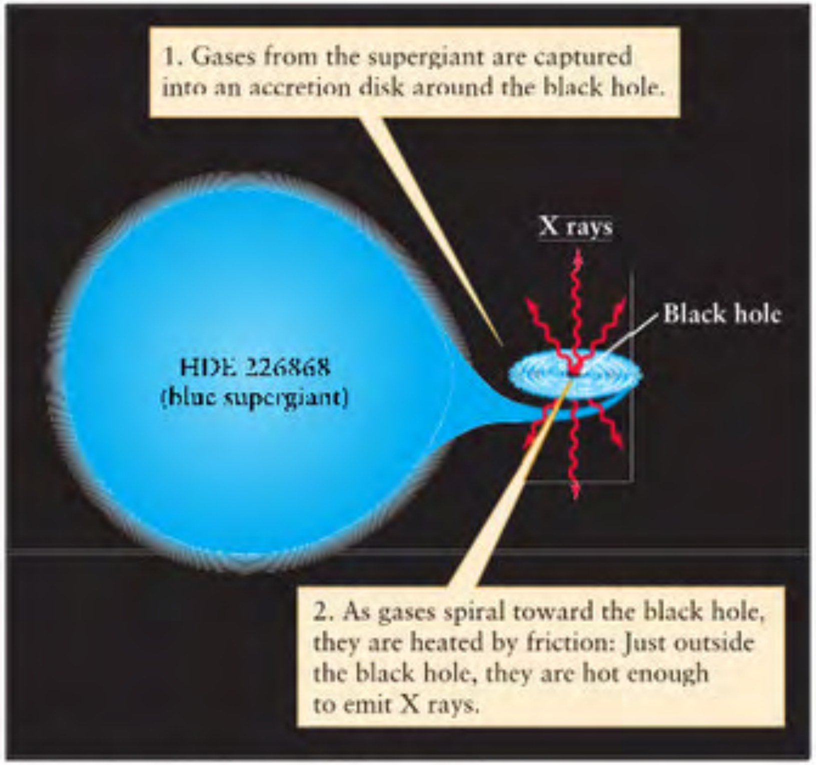
The X-ray emission of Cygnus X-1 changes significantly within 0.01 sec. This places a limit on the size of the object.

The shortest variation time in the flux of an object of size D is the time that light takes to travel across the object (t_{lc}).

$t_{variation} > t_{lc} = D/c \rightarrow D < ct_{variation} \rightarrow$
$\rightarrow D < 3\times10^5$ km/sec $\times$ 0.01 sec
$\rightarrow D < 3{,}000$ km

HDE 226868 is a B0 star with an estimated mass of 30 $M_\odot$ and the other object in the binary is estimated to have a mass of ~ $7M_\odot$ implying that it is a black hole.

Cygnus X-1



(a) A schematic diagram of Cygnus X-1

(b) An artist's impression of Cygnus X-1

What have we learned?

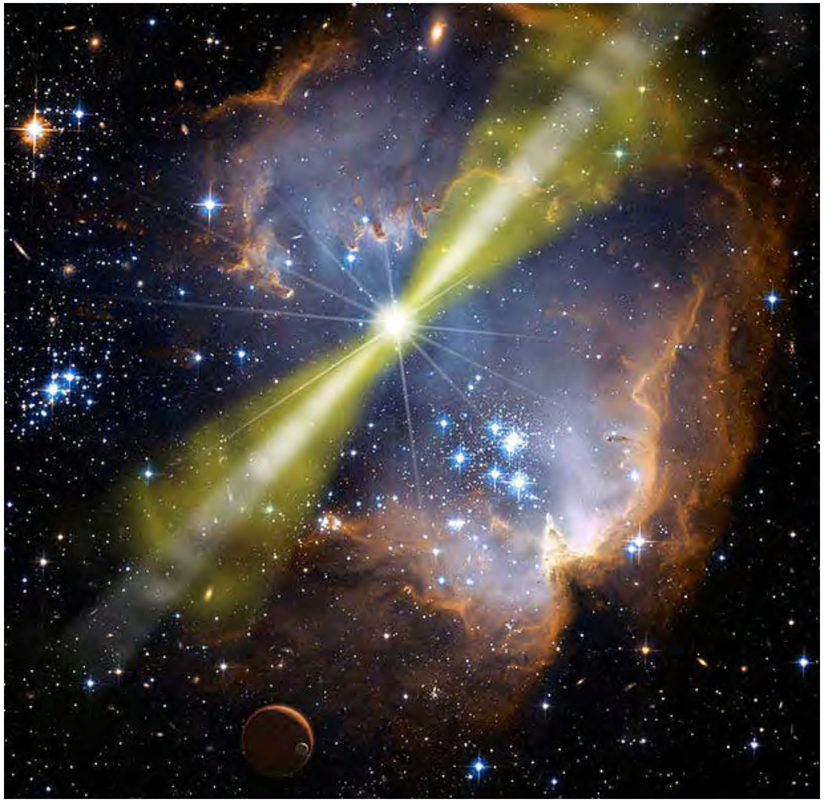
- **What is a black hole?**
  - A black hole is a massive object whose radius is so small that the escape velocity exceeds the speed of light.
- **What would it be like to visit a black hole?**
  - You can orbit a black hole like any other object of the same mass—black holes don't suck!
  - Near the event horizon, time slows down and tidal forces are very strong.

What have we learned?

- **Do black holes really exist?**
  – Some X-ray binaries contain compact objects too massive to be neutron stars—they are almost certainly black holes.

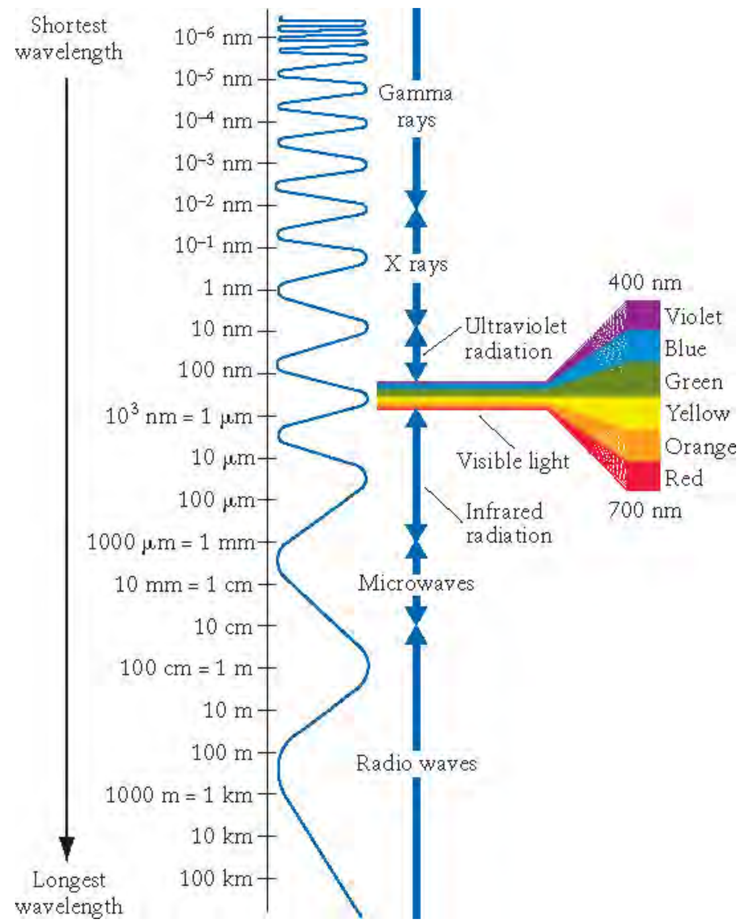
18.4 The Origin of Gamma-Ray Bursts

- Our goals for learning:
  - **What causes gamma-ray bursts?**



Gamma-Ray Astronomy

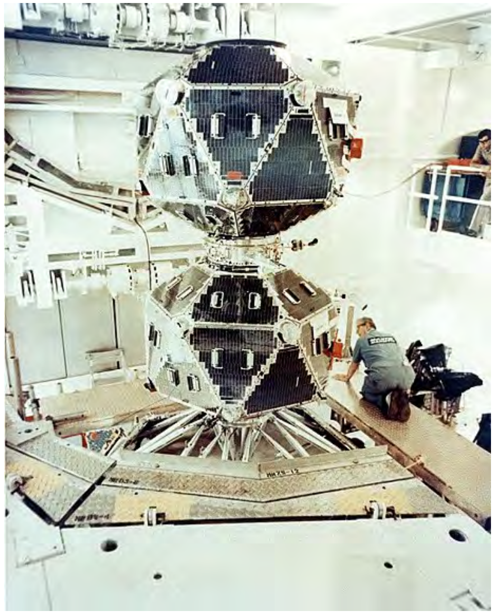
Gamma rays are photons with energies > 100 keV and are produced by sub-atomic particle interactions. They are absorbed by our atmosphere making observations from satellites necessary.



Gamma-Ray Bursts

Unexpected Discoveries of the Cold War Era
Gamma-ray bursts were first observed in the late 1960s by the U.S. Vela satellites, which were built to detect gamma radiation pulses emitted by nuclear weapons tested in space.

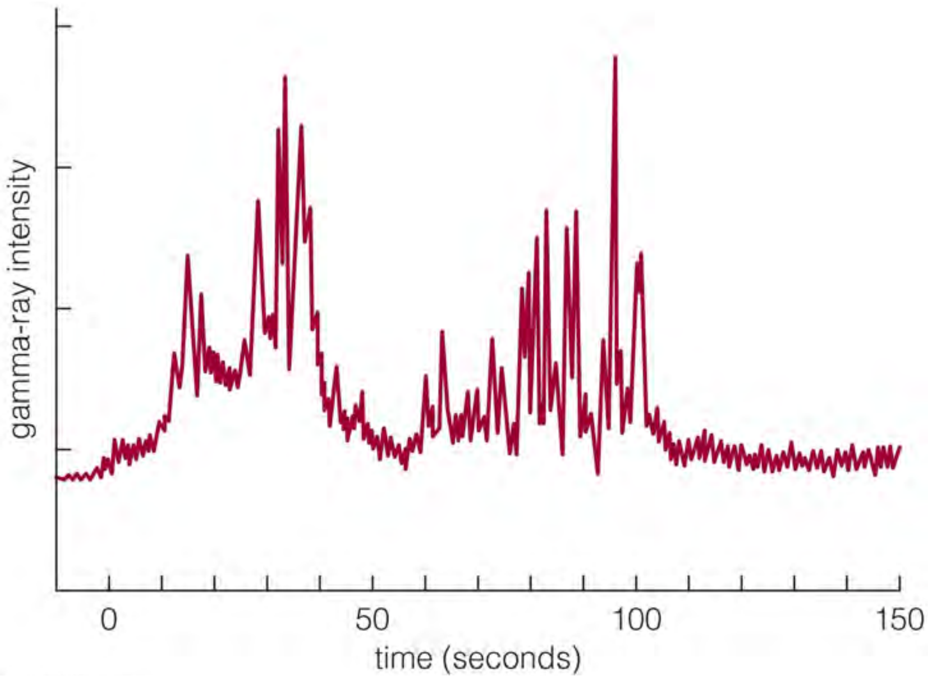
A team at Los Alamos was able to determine rough estimates for the sky positions of several bursts and definitively rule out a terrestrial or solar origin.



VELA 5A, 5B

The discovery was declassified and published in 1973 as an Astrophysical Journal article entitled "*Observations of Gamma-Ray Bursts of Cosmic Origin*"

Gamma-Ray Bursts



- Brief bursts of gamma rays coming from space were first detected in the 1960s.

Gamma-Ray Astronomy

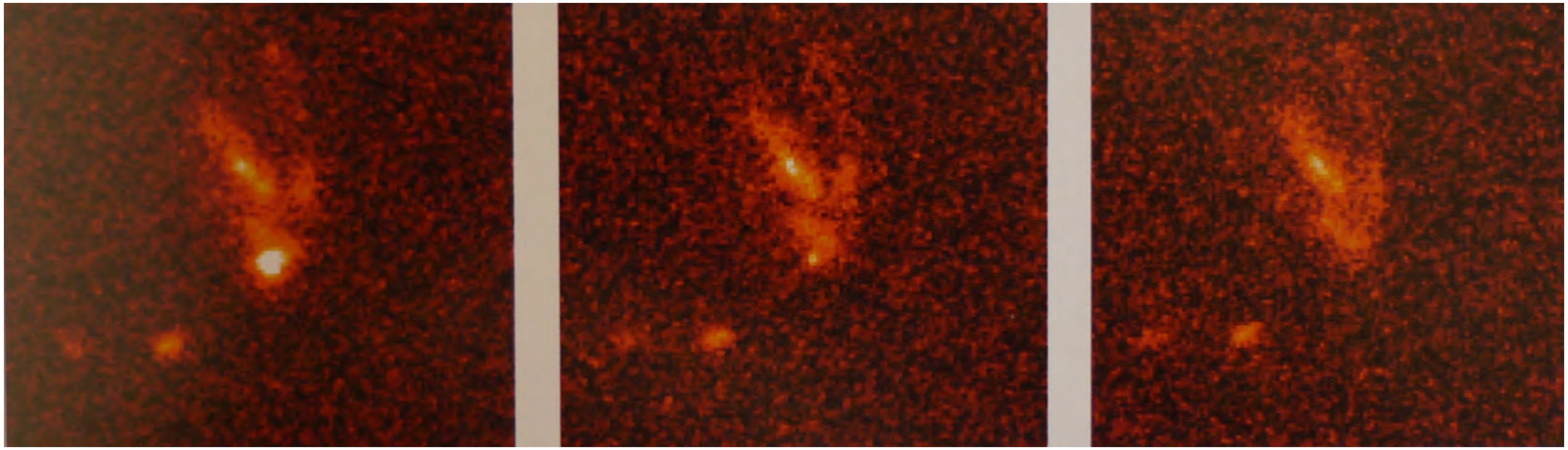
One of the most important gamma- ray telescopes placed in orbit in 1991 was the **Compton Gamma-ray Observatory** (CGRO).

The **EGRET** instrument conducted the first all sky survey above 100 MeV. Using four years of data it discovered 271 sources.

The Burst and Transient Source Experiment (**BATSE**) instrument (20-600keV) made about 2700 GRB detections.

Instruments on CGRO were EGRET, BATSE, OSSE, and COMPTEL.
Energy range (20 keV - 30 GeV).

Gamma-Ray Bursts

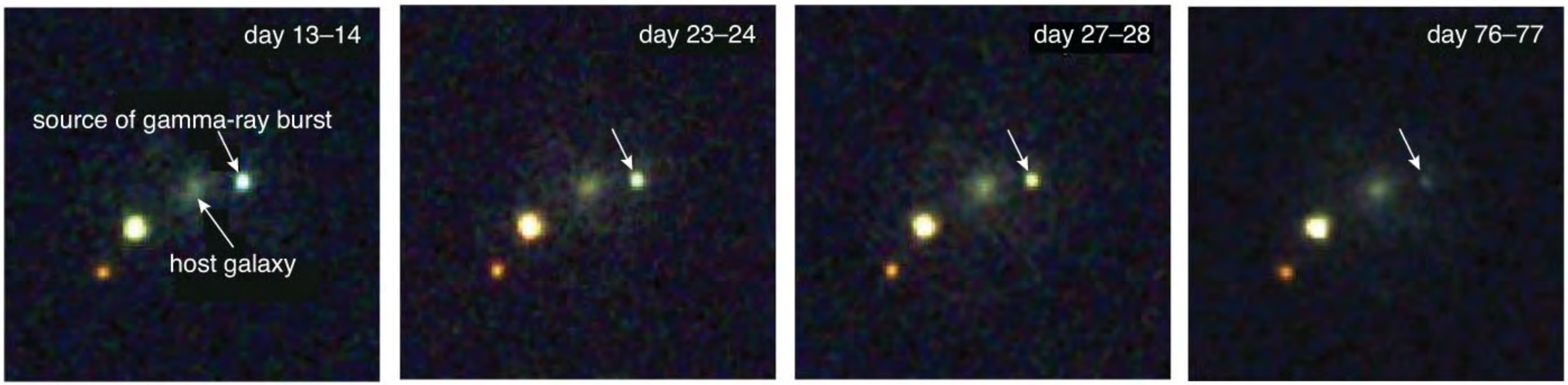


(a) (b) (c)

Optical observations in the locations where GRBs went off showed that they originate mostly in spiral galaxies.

The ultraluminous GRB 990123 was located on the outskirts of a star-forming galaxy with a redshift of 1.6. The Hubble Space Telescope images show the afterglow at (a)16, (b) 59 and (c) 380 days after the burst.

Supernovae and Gamma-Ray Bursts

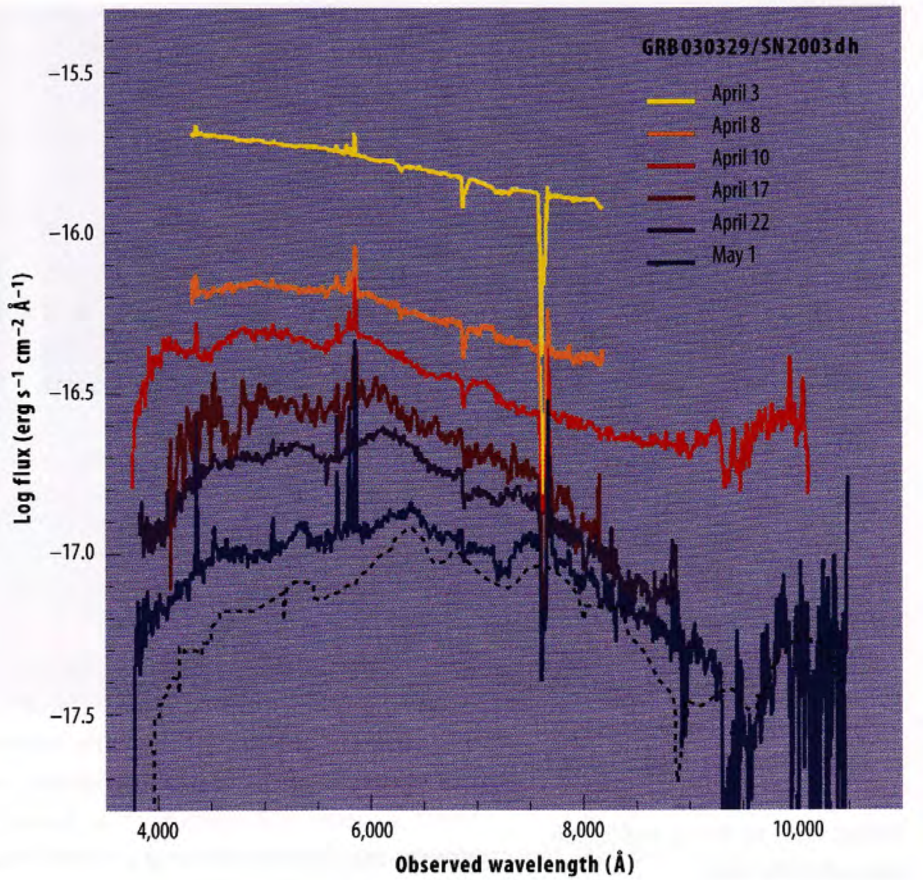


- Observations show that at least some gamma-ray bursts are produced by supernova explosions.
- Others may come from collisions between neutron stars.

Supernovae and Gamma-Ray Bursts

Follow up of several GRBs with optical spectral observations showed spectra that resembled those of supernovae.

As the optical afterglow of GRB 030329 faded, the spectrum of the underlying supernova, SN 2003dh, became visible. After 34 days its spectrum resembled that of the supernova SN 1998bw of a similar age (dashed line).



Collapsar Model

The **collapsar model** proposes that a long gamma ray burst occurs during a core collapse supernova (Type Ic) of a ~ 30 $M_{\odot}$ star that is spinning rapidly.

In this model the core of the star collapses to form a black hole. The material just around the black hole forms an accretion disk. The magnetic field of this accretion disk forms jets of charged particles that break through the outer layers of the star.

(**Key point**: in a Type Ic supernova the outer H and He layers have been blown away so it's easier for the jets to break through the star)

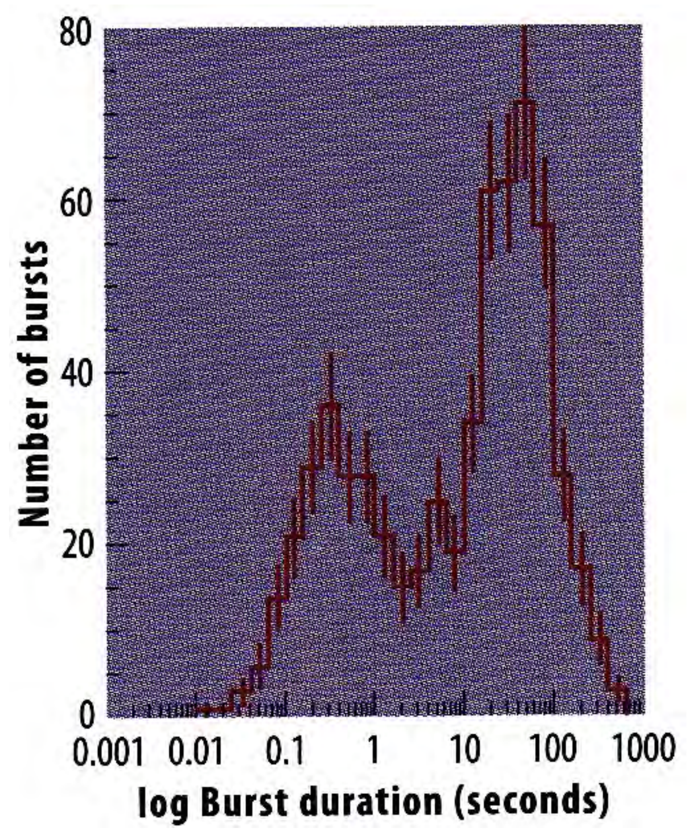
The energetic particles in the jet produce gamma-rays. If a jet is pointed towards the Earth we see a gamma ray burst.

The accretion disk is sucked into the BH within a few seconds and the gamma-rays burst ends.

Long and Short GRBs

Gamma-ray bursts fall into two types. Long bursts ~ 2 - 1000 sec duration and short bursts ~ 0.01 sec - 2 sec duration (contain lower energy photons than long bursts)

Their cosmic origin was confirmed with the measurement of their redshift. The spectrum of the afterglow of long bursts is consistent with a Type Ic supernova spectrum.

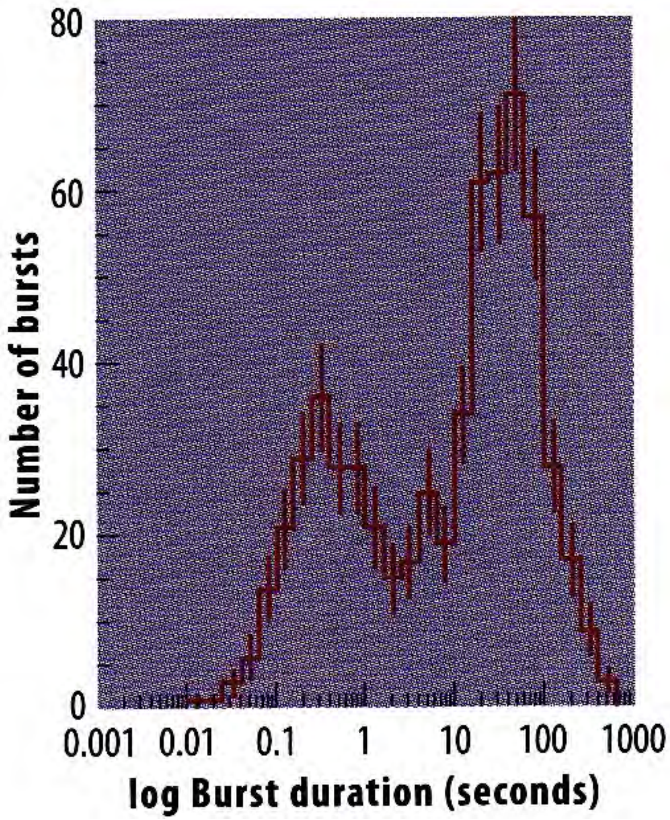


Progenitors of Long GRBs

Long GRBs are found in systems with abundant recent star formation (ie. contain massive stars) , such as in irregular galaxies and in the arms of spiral galaxies.

Why are star formation regions likely to contain massive stars?

Follow up observations of several long GRBs have detected emission from type Ib/c supernova at the same location.

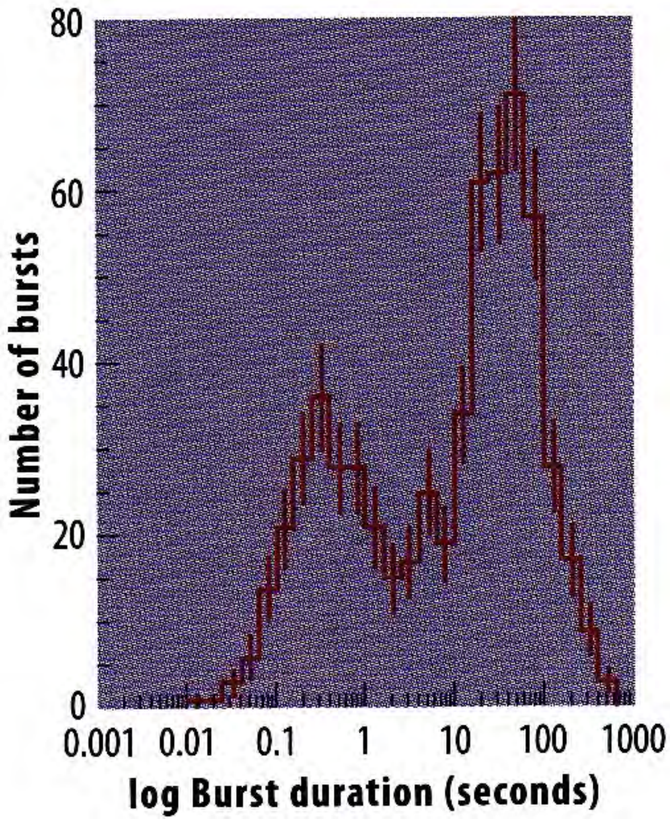


Progenitors of Short GRBs

Several short GRBs have been associated with the outer regions and even the outer halo of large **elliptical galaxies** in which star formation has nearly ceased.

All the hosts identified so far have also been at low redshift.

No supernova has been associated with any short GRB.

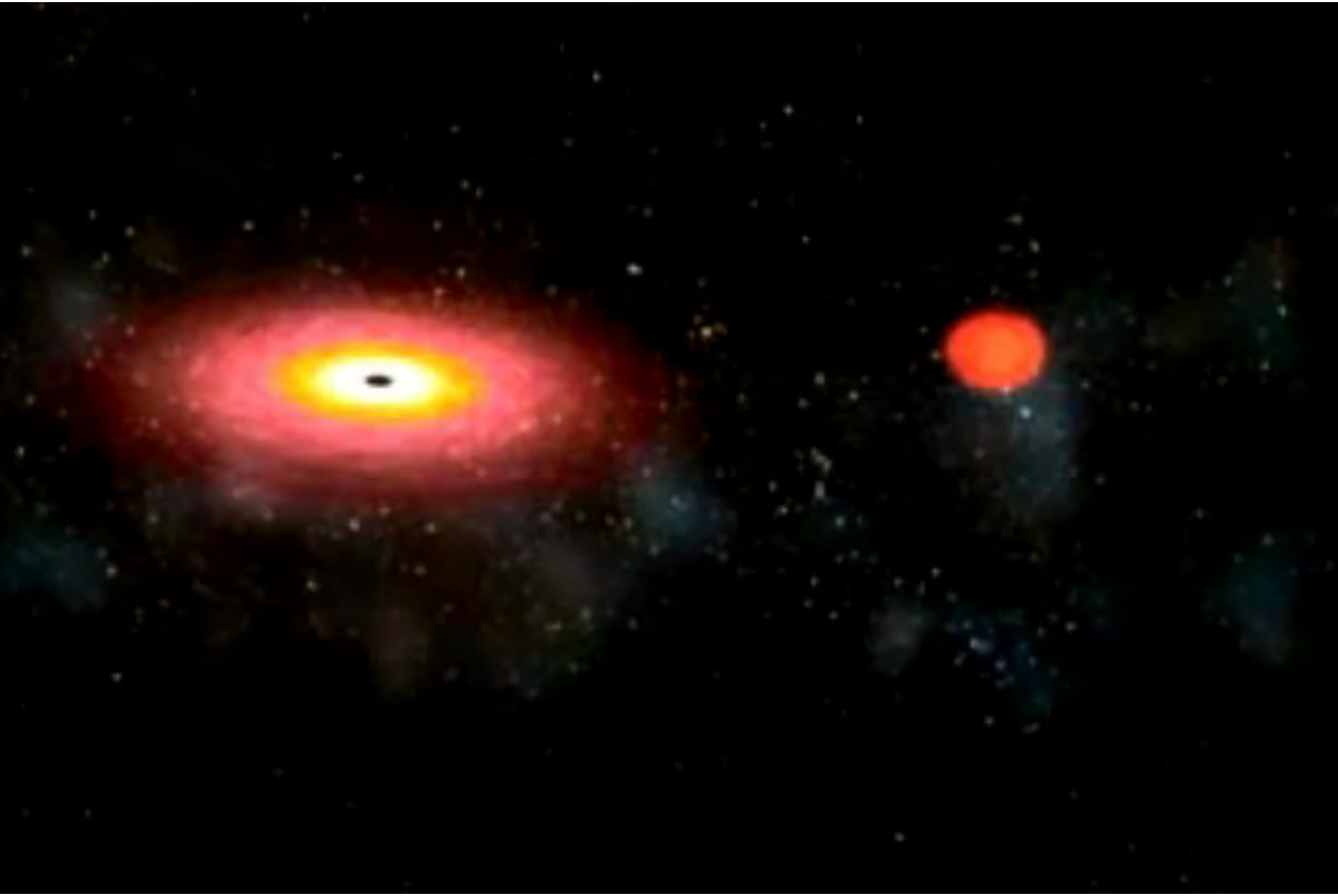


Models of Short GRBs

One model posits that short GRBs are the result of the merger of two compact objects : two neutron stars, or a black hole and a neutron star.

During the merger immense amount of energy is liberated before the matter plunges into a single black hole.

The whole process is believed to occur extremely quickly and be completely over within a few seconds, accounting for the short nature of these bursts.



What have we learned?

- **What causes gamma-ray busts?**
  – Most gamma-ray bursts come from distant galaxies.
  – They must be among the most powerful explosions in the universe, probably signifying the formation of black holes.
  – At least some gamma-ray bursts come from supernova explosions, others possibly from the mergers of neutron stars and black holes.