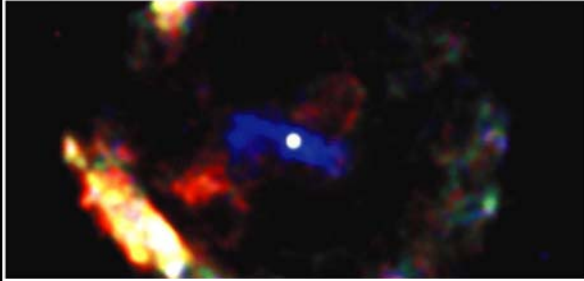


Chapter 18 The Bizarre Stellar Graveyard



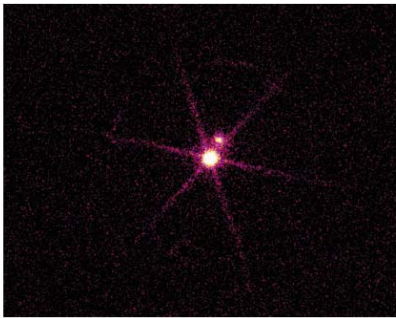
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18.1 White Dwarfs

- Our goals for learning
- What is a white dwarf?
- What can happen to a white dwarf in a close binary system?

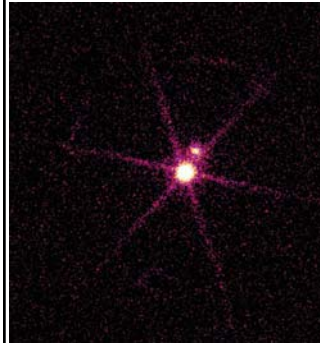
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What is a white dwarf?



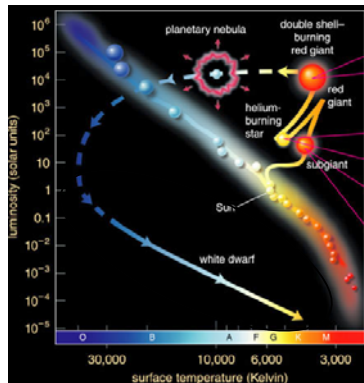
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White Dwarfs



- White dwarfs are the remaining cores of dead stars
- Electron degeneracy pressure supports them against gravity

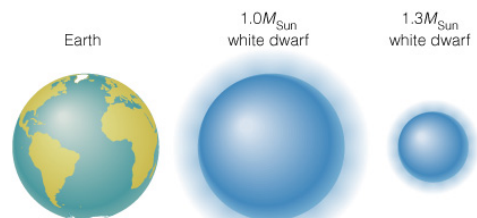
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White dwarfs cool off and grow dimmer with time

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Size of a White Dwarf



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

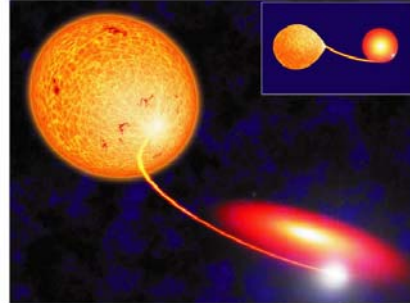
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The White Dwarf Limit

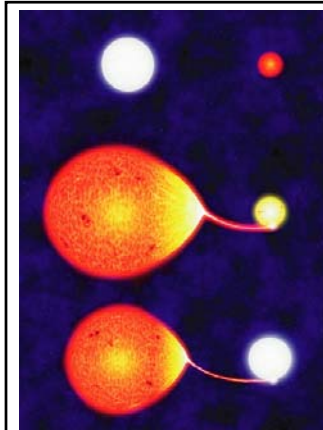
- Quantum mechanics says that electrons must move faster as they are squeezed into a very small space
- As a white dwarf's mass approaches $1.4M_{\text{Sun}}$, its electrons must move at nearly the speed of light
- Because nothing can move faster than light, a white dwarf cannot be more massive than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

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



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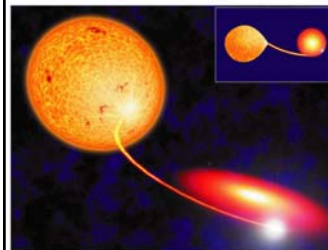
Star that started with less mass gains mass from its companion

Eventually the mass-losing star will become a white dwarf

What happens next?

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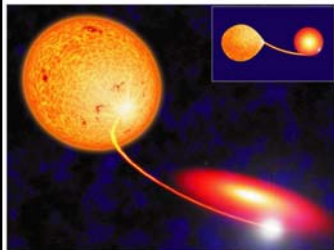
Accretion Disks



- 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*

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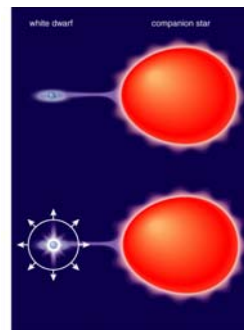
Accretion Disks



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

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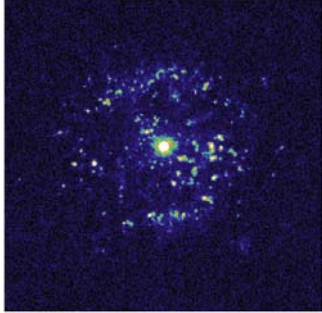
Nova



- The temperature of accreted matter eventually becomes hot enough for hydrogen fusion
- Fusion begins suddenly and explosively, causing a *nova*

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Nova



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

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Two Types of Supernova

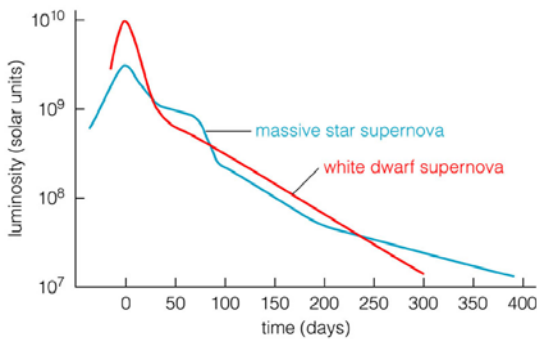
Massive star supernova:

Iron core of massive star reaches white dwarf limit and collapses into a neutron star, causing explosion

White dwarf supernova:

Carbon fusion suddenly begins as white dwarf in close binary system reaches white dwarf limit, causing total explosion

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

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Nova or Supernova?

- Supernovae are MUCH MUCH more luminous!!! (about 10 million times)
- Nova: H to He fusion of a layer of accreted matter, white dwarf left intact
- Supernova: complete explosion of white dwarf, nothing left behind

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Supernova Type: Massive Star or White Dwarf?

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

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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

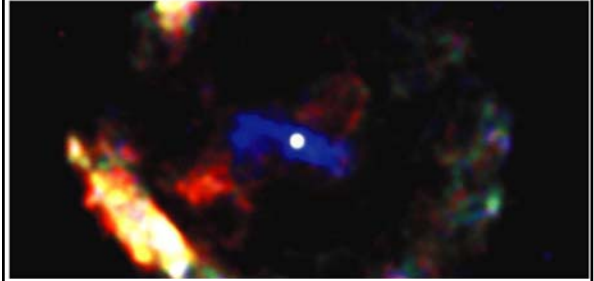
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18.2 Neutron Stars

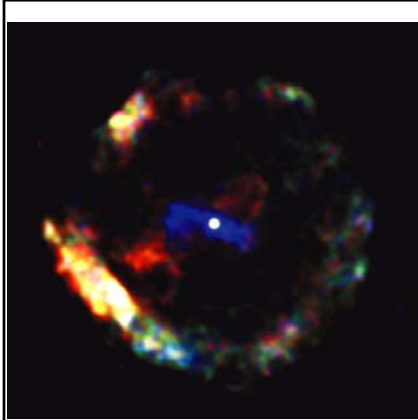
- Our goals for learning
- What is a neutron star?
- How were neutron stars discovered?
- What can happen to a neutron star in a close binary system?

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What is a neutron star?



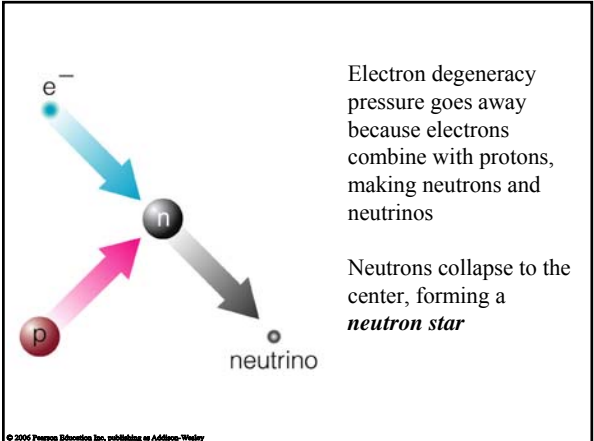
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A neutron star is the ball of neutrons left behind by a massive-star supernova

Degeneracy pressure of neutrons supports a neutron star against gravity

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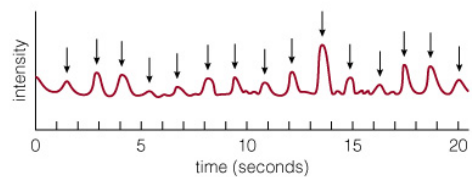
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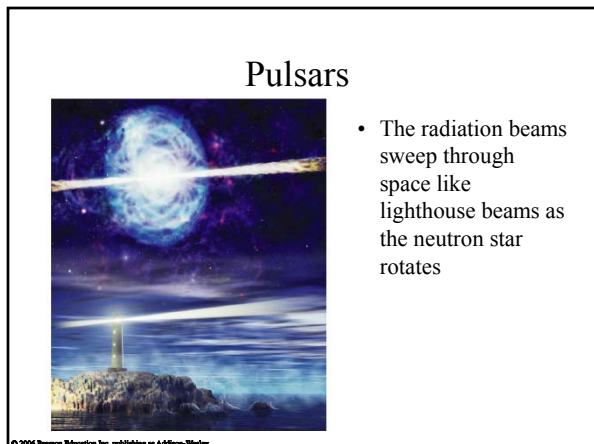
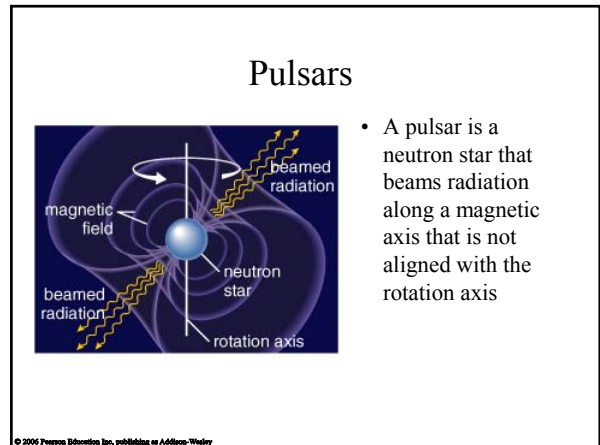
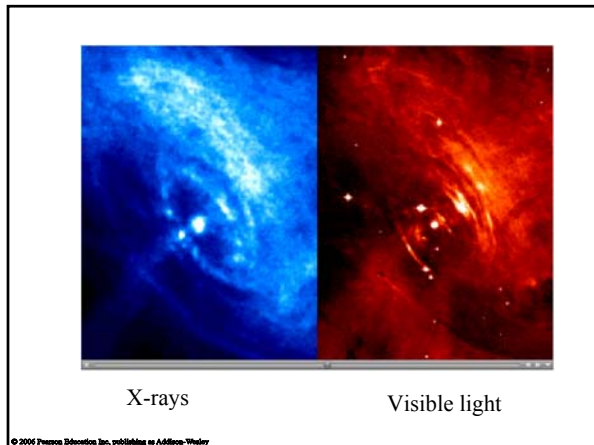
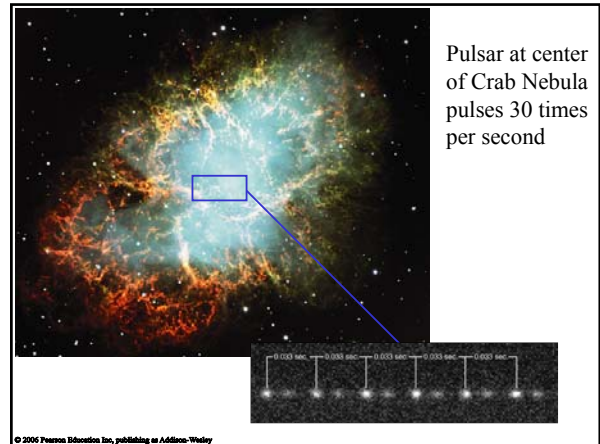
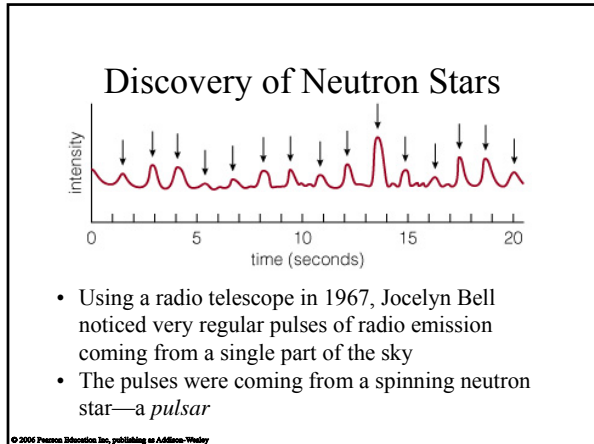
A neutron star is about the same size as a small city

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How were neutron stars discovered?



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Why Pulsars must be Neutron Stars

Circumference of NS = 2π (radius) \sim 60 km


Spin Rate of Fast Pulsars \sim 1000 cycles per second

Surface Rotation Velocity \sim 60,000 km/s
 \sim 20% speed of light
 \sim escape velocity from NS

Anything else would be torn to pieces!

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Collapse of the Solar Nebula

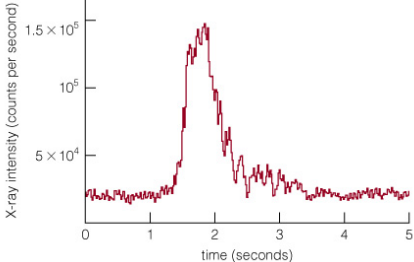


Pulsars spin fast because core's spin speeds up as it collapses into neutron star

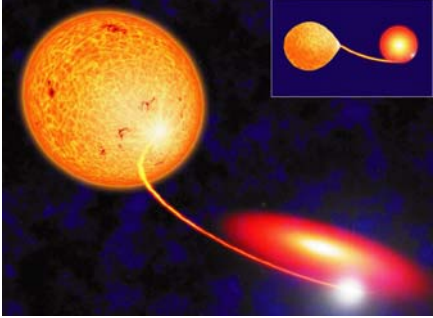
Conservation of angular momentum

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

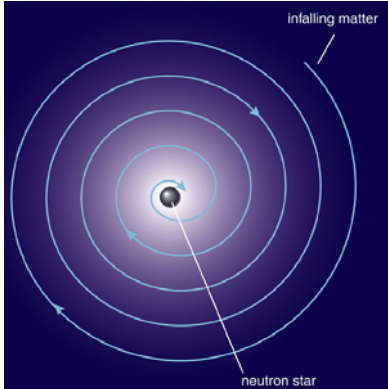


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Matter falling toward a neutron star forms an accretion disk, just as in a white-dwarf binary

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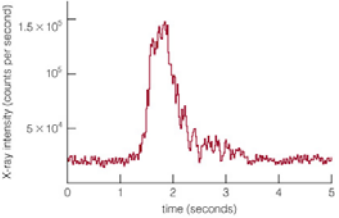


Accreting matter adds angular momentum to a neutron star, increasing its spin

Episodes of fusion on the surface lead to X-ray bursts

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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

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What have we learned?

- **What is a neutron star?**
 - 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

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What have we learned?

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

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18.3 Black Holes: Gravity's Ultimate Victory

- Our goals for learning
- What is a black hole?
- What would it be like to visit a black hole?
- Do black holes really exist?

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What is a black hole?



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

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Escape Velocity

Initial Kinetic Energy = Final Gravitational Potential Energy

$$\frac{(\text{escape velocity})^2}{2} = \frac{G \times (\text{mass})}{(\text{radius})}$$

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Relationship Between Escape Velocity and Planetary Radius

Escape Velocity of Imaginary Planet Having the Mass of Earth

Radius of Imaginary Planet: 1 cm 6,000 km

Radius: x 10 km

x 10 R_{Earth}

Mass of Planet = Mass of Earth

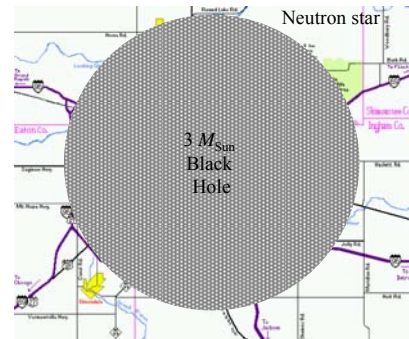
Escape velocity = km/s = % the speed of light

Light would not be able to escape Earth's surface if you could shrink it to < 1 cm

“Surface” of a Black Hole

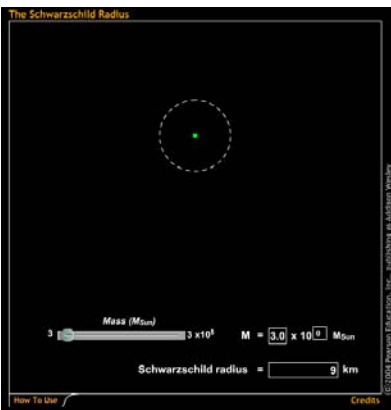
- The “surface” of a black hole is the radius at which the escape velocity equals the speed of light.
- This spherical surface is known as the *event horizon*.
- The radius of the event horizon is known as the *Schwarzschild radius*.

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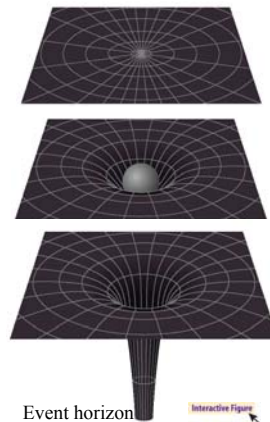
The event horizon of a $3 M_{\text{Sun}}$ black hole is also about as big as a small city

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Event horizon is larger for black holes of larger mass

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

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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.

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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 $3 M_{\text{sun}}$
- Some massive star supernovae can make black hole if enough mass falls onto core

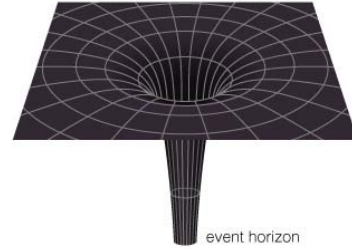
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Singularity

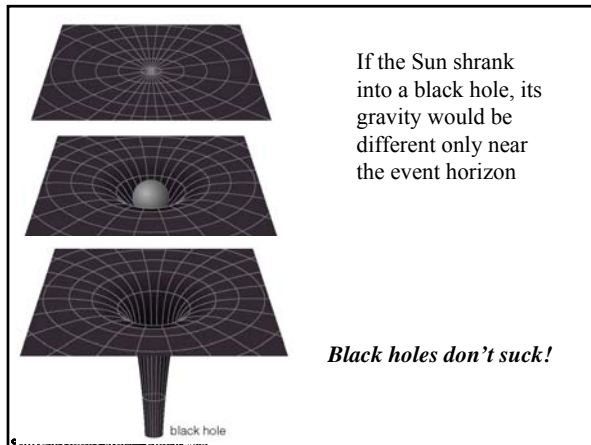
- Beyond the neutron star limit, no known force can resist the crush of gravity.
- As far as we know, gravity crushes all the matter into a single point known as a *singularity*.

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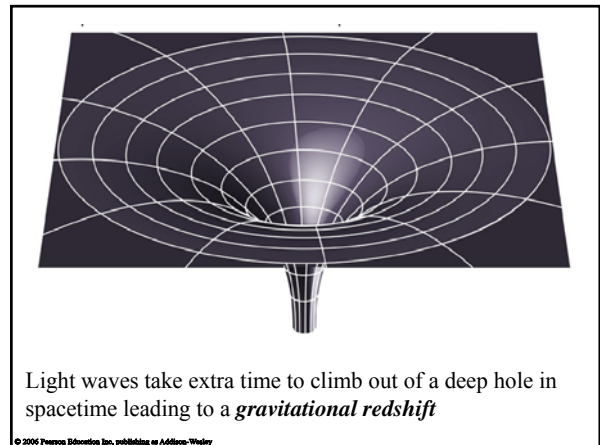
What would it be like to visit a black hole?



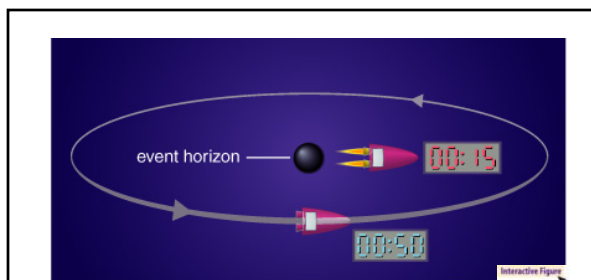
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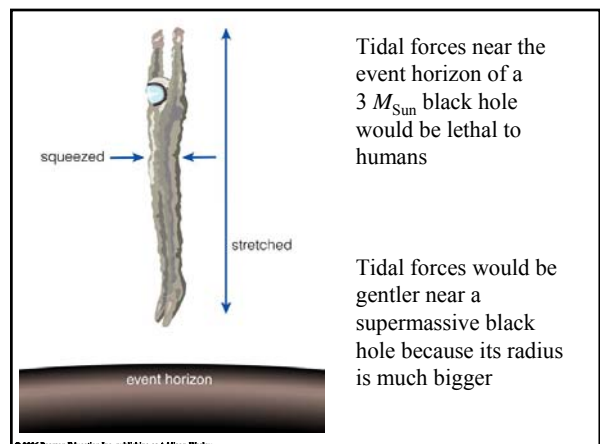


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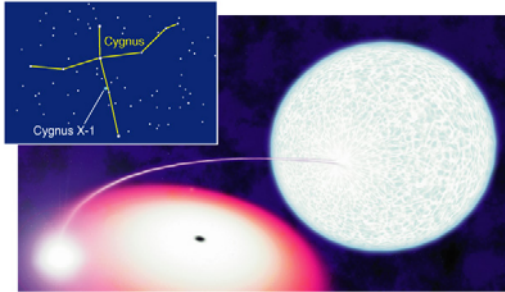
Time passes more slowly near the event horizon

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Do black holes really exist?

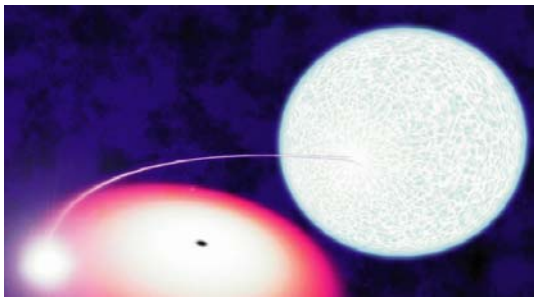


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Black Hole Verification

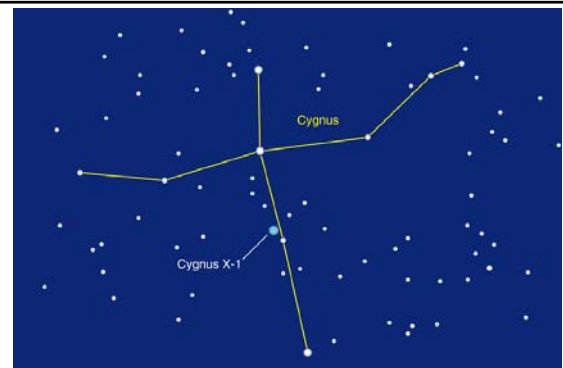
- Need to measure mass
 - Use orbital properties of companion
 - Measure velocity and distance of orbiting gas
- It's a black hole if it's not a star and its mass exceeds the neutron star limit ($\sim 3 M_{\text{Sun}}$)

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Some X-ray binaries contain compact objects of mass exceeding $3 M_{\text{Sun}}$ which are likely to be black holes

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

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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

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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

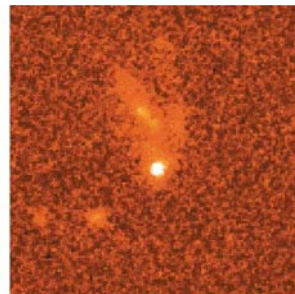
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18.4 The Mystery of Gamma Ray Bursts

- Our goals for learning
- Where do gamma-ray bursts come from?
- What causes gamma-ray bursts?

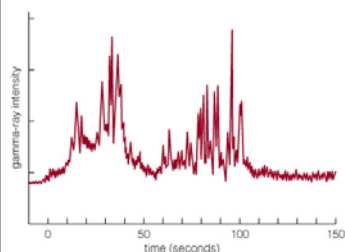
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Where do gamma-ray bursts come from?



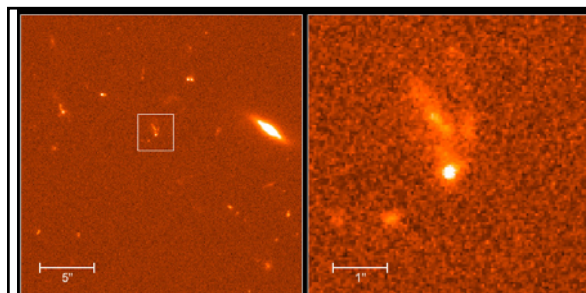
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Gamma-Ray Bursts



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

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- Observations in the 1990s showed that many gamma-ray bursts were coming from very distant galaxies
- They must be among the most powerful explosions in the universe—could be the formation of a black hole

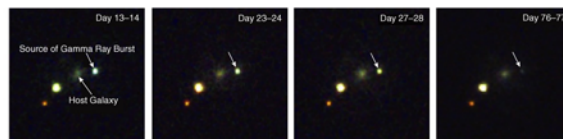
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What causes gamma-ray bursts?



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Supernovae and Gamma-Ray Bursts



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

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What have we learned?

- Where do gamma-ray bursts come from?
 - 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
- What causes gamma-ray bursts?
 - At least some gamma-ray bursts come from supernova explosions

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