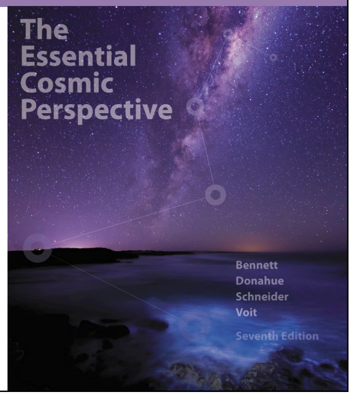
Lecture Outline

Chapter 14: The Bizarre Stellar Graveyard

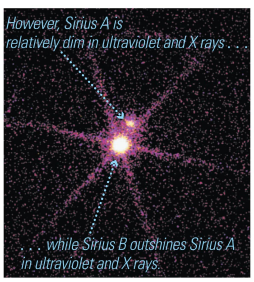


14.1 White Dwarfs

Our goals for learning:

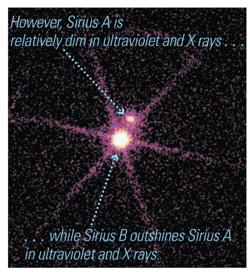
- What is a white dwarf?
- What can happen to a white dwarf in a close binary system?

•What is a white dwarf?



b Sirius as seen by the Chandra X-Ray Telescope.

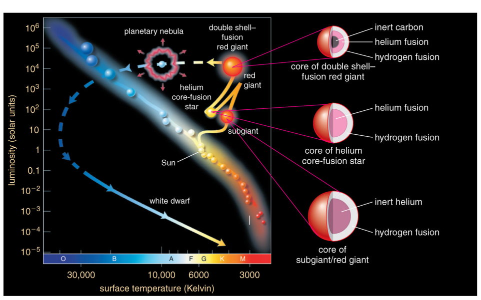
White Dwarfs



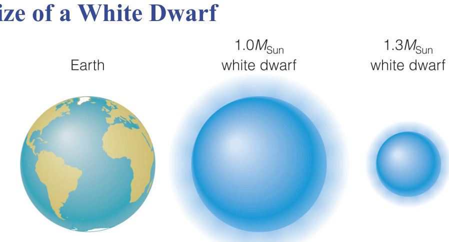
b Sirius as seen by the Chandra X-Ray Telescope.

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

White dwarfs cool off and grow dimmer with time.



Size of a White Dwarf

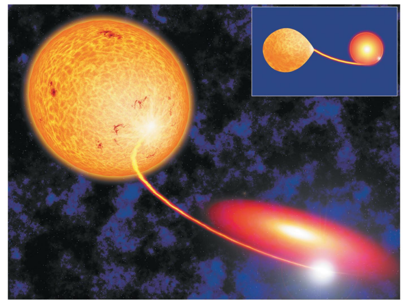


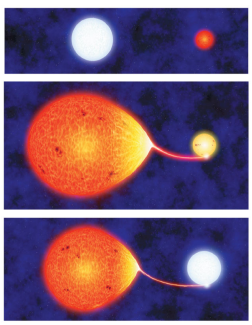
- White dwarfs with the same mass as the Sun are about the same size as Earth.
- Higher-mass white dwarfs are smaller.

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* (also known as the *Chandrasekhar limit*).

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



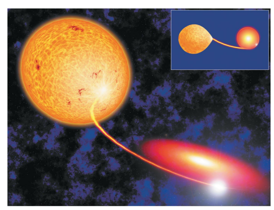


A star that started with less mass gains mass from its companion.

Eventually, the mass-losing star will become a white dwarf.

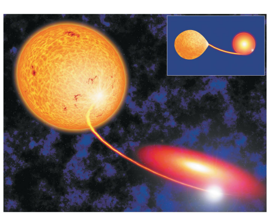
What happens next?

Accretion Disks



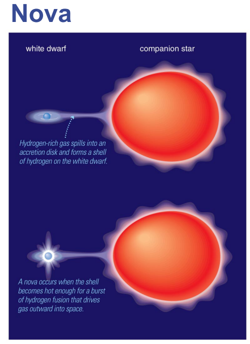
- Mass falling toward a white dwarf from its close binary companion has some angular momentum.
- The matter therefore orbits the white dwarf in an *accretion disk*.

Accretion Disks



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

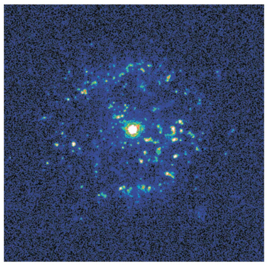
Nova



a Diagram of the nova process.

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

Nova

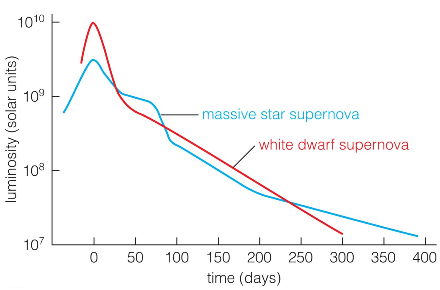


b Hubble Space Telescope image showing blobs of gas ejected from the nova T Pyxidis. The bright spot at the center of the blobs is the binary star system that generated the nova.

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

Two Types of Supernova

- **Massive star supernova:**
  - Iron core of massive star reaches white dwarf limit and collapses into a neutron star, causing an explosion.
- ***White dwarf supernova:***
  - Carbon fusion suddenly begins as white dwarf in close binary system reaches white dwarf limit, causing a total explosion.



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

Nova or Supernova?

- Supernovae are MUCH MUCH more luminous than novae (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

Supernova Types: Massive Star or White Dwarf?

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

What have we learned?

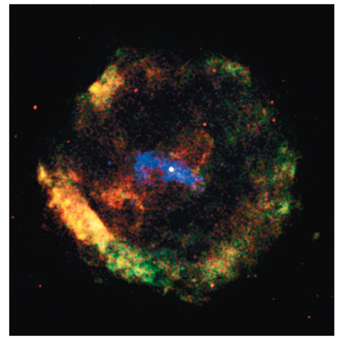
- What is a white dwarf?
  - A white dwarf is the inert core of a dead star.
  - Electron degeneracy pressure balances the inward pull of gravity.
- What can happen to a white dwarf in a close binary system?
  - Matter from its close binary companion can fall onto the white dwarf through an accretion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

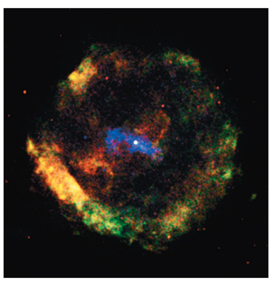
14.2 Neutron Stars

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?

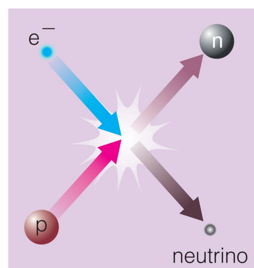
•What is a neutron star?





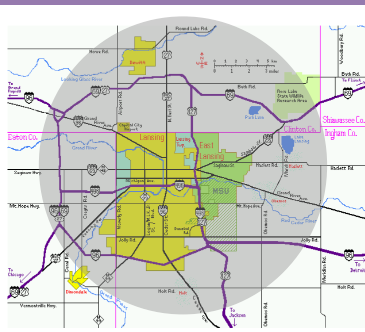
A neutron star is the ball of neutrons left behind by a massive-star supernova.

The degeneracy pressure of neutrons supports a neutron star against gravity.



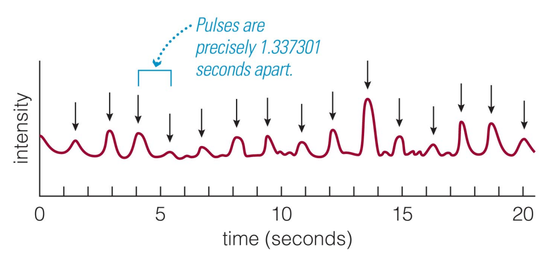
Electron degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos.

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

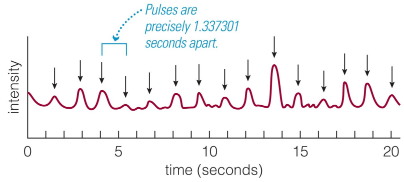


A neutron star is about the same size as a small city.

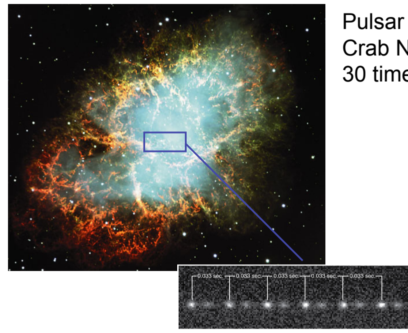
•How were neutron stars discovered?



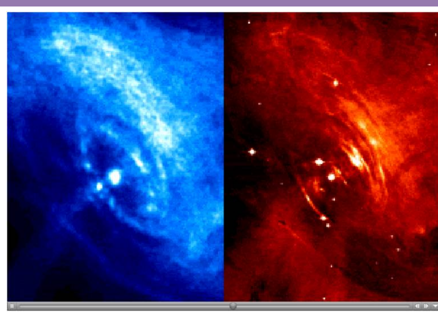
Discovery of Neutron Stars



- 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*.



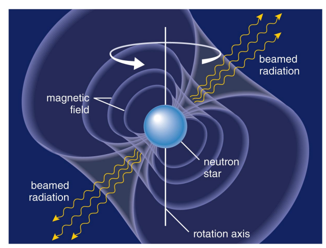
Pulsar at center of Crab Nebula pulses 30 times per second



X rays   Visible light

PLAY Crab Nebula Movie-CHANDRA

Pulsars



a A pulsar is a rotating neutron star that beams radiation along its magnetic axis.

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

Pulsars

b If the magnetic axis is not aligned with the rotation axis, the pulsar's beams sweep through space like lighthouse beams. Each time one of the pulsar's beams sweeps across Earth, we see a pulse of radiation.

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

Why Pulsars Must Be Neutron Stars

Circumference of Neutron Star = 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!

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

Conservation of angular momentum

PLAY Collapse of the Solar Nebula

Thought Question

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

A. Yes

B. No

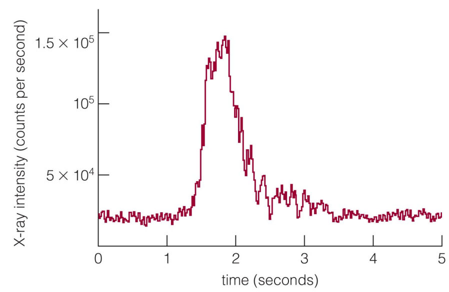
Thought Question

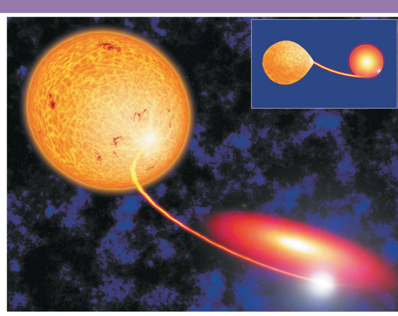
Could there be neutron stars that appear as pulsars to other civilizations but not to us?

A. Yes

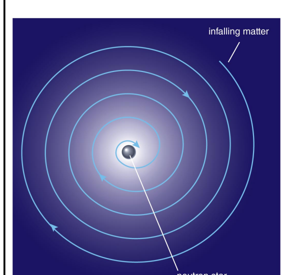
B. No

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





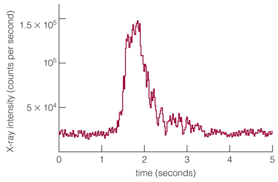
Matter falling toward a neutron star forms an accretion disk, just as in a white dwarf binary.



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

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

X-Ray Bursts



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

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 $3M_{Sun}$.

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.

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.

14.3 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?

•What is a black hole?

c The curvature of spacetime becomes greater and greater as we approach a black hole, and a black hole itself is a bottomless pit in spacetime.

What is a black hole?

- A ***black hole*** is an object whose gravity is so powerful that not even light can escape it.
- Some massive star supernovae can make a black hole if enough mass falls onto the core.

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.

Thought Question

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

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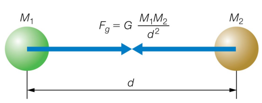
C. It stays the same.

Hint:



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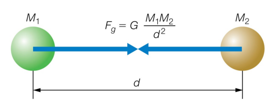
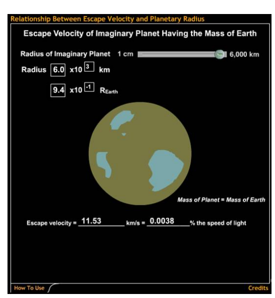


Escape Velocity

change in kinetic energy = change in gravitational potential energy

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

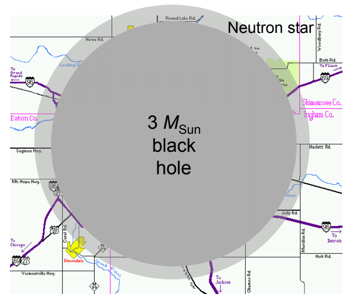


Light would not be able to escape Earth's surface if you could shrink it to <1 cm.

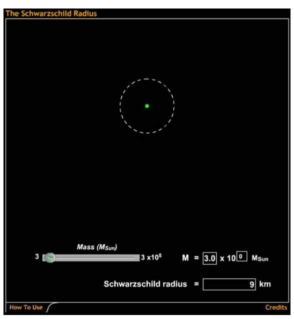
PLAY Relationship Between Escape Velocity and Planetary Radius

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.***



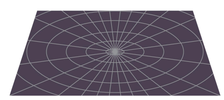
The event horizon of a $3M_{Sun}$ black hole is also about as big as a small city.



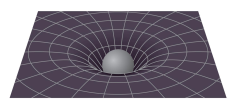
Event horizon is larger for black holes of larger mass.

PLAY The Schwarzschild Radius

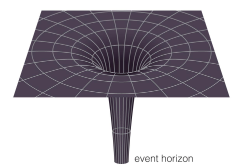
A black hole's mass strongly warps space and time in the vicinity of the event horizon.



a A two-dimensional representation of "flat" spacetime. The distances between adjacent circles are the same.



b Gravity arises from curvature of spacetime, represented here by a mass pushing down on the rubber sheet. Notice how the circles become more widely separated near the mass, showing that the curvature is greater as we approach the mass on the sheet.



c The curvature of spacetime becomes greater and greater as we approach a black hole, and a black hole itself is a bottomless pit in spacetime.

MA INTERACTIVE FIGURE

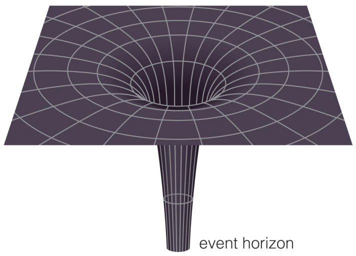
No Escape

- 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's mass, changes its spin or charge, but otherwise loses its identity.

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.***

•What would it be like to visit a black hole?



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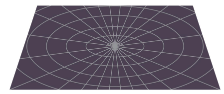

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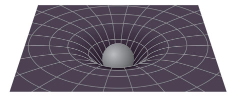
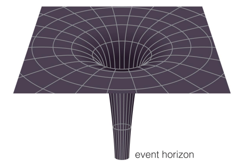


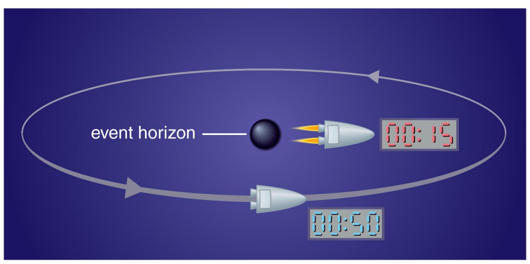
b Gravity arises from curvature of spacetime, represented here by a mass pushing down on the rubber sheet. Notice how the circles become more widely separated near the mass, showing that the curvature is greater as we approach the mass on the sheet.

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

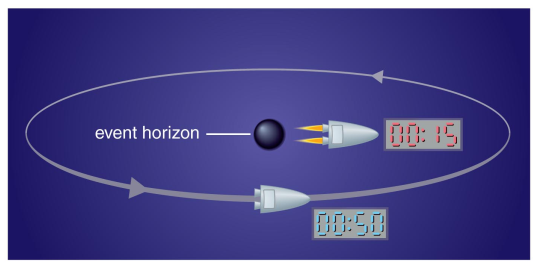


c The curvature of spacetime becomes greater and greater as we approach a black hole, and a black hole itself is a bottomless pit in spacetime.

Black holes don't suck!



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



MA INTERACTIVE FIGURE

Time passes more slowly near the event horizon.

Thought Question

Is it easy or hard to fall into a black hole?

A. Easy
B. Hard

Thought Question

Is it easy or hard to fall into a black hole?

A. Easy
B. Hard

(*Hint*: A black hole with the same mass as the Sun wouldn't be much bigger than a college campus.)

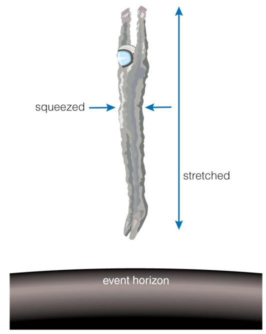
Thought Question

Is it easy or hard to fall into a black hole?

A. Easy

B. Hard

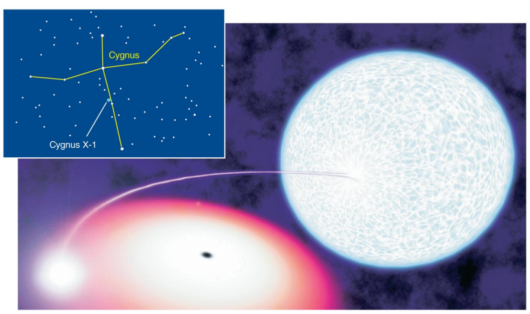
(*Hint*: A black hole with the same mass as the Sun wouldn't be much bigger than a college campus.)



Tidal forces near the event horizon of a $3M_{Sun}$ black hole would be lethal to humans.

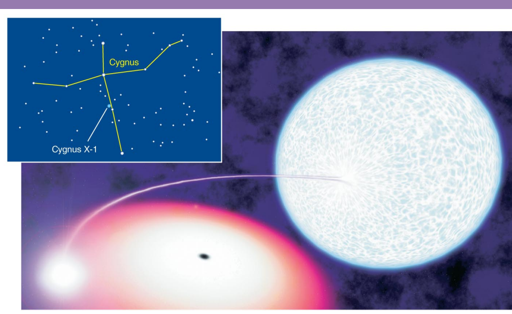
Tidal forces would be gentler near a supermassive black hole because its radius is much bigger.

•Do black holes really exist?

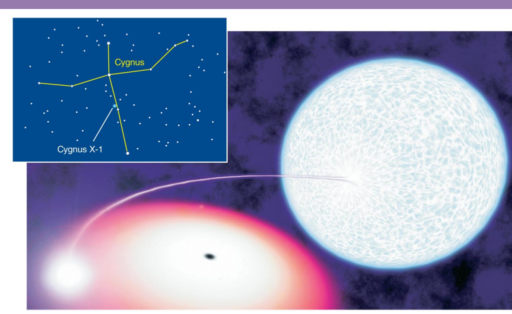


Black Hole Verification

- 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 (~$3M_{Sun}$).



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



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

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?

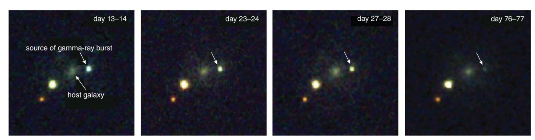
- Do black holes really exist?
  - Some X-ray binaries contain compact objects too massive to be neutron stars—they are almost certainly black holes.

14.4 The Origin of Gamma-Ray Bursts

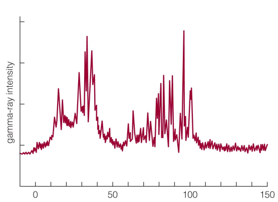
Our goals for learning:

- What causes gamma-ray bursts?

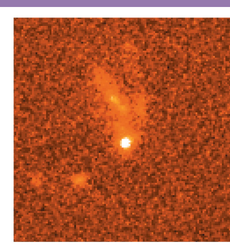
•What causes gamma-ray bursts?



Gamma-Ray Bursts

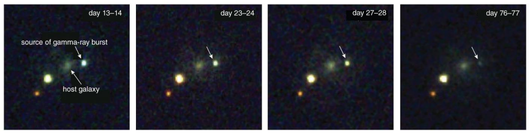


- Brief bursts of gamma rays coming from space were first detected in the 1960s.



- 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 black holes.

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.

What have we learned?

- What causes gamma-ray bursts?
  - Gamma-ray bursts are among the most powerful explosions in the universe and probably signify the formation of black holes.
  - At least some gamma-ray bursts come from supernova explosions in distant galaxies.