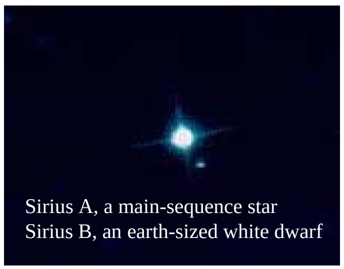
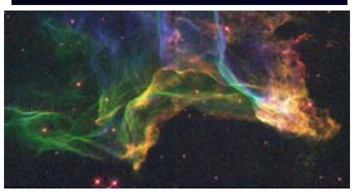
White Dwarfs, Neutron Stars, & Black Holes


Sirius A, a main-sequence star
Sirius B, an earth-sized white dwarf

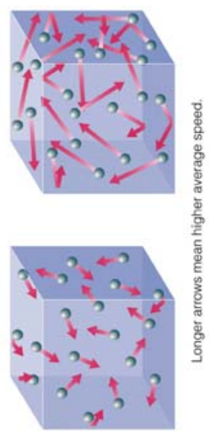

Cygnus Loop
Supernova 20,000 yr ago

- When the sun dies, it becomes a white dwarf. Why is a white dwarf different from a main-sequence star?
- What causes pressure?
  - In a main-sequence star, gas particles moves because they are hot. (Normal gas)
  - In a WD, electrons move because they are close to each other. (Degenerate gas)
- Neutron star
- Black hole

- Homework 6 is due Thurs, 2 April at 6:00am
- OBAFGKM extra credit
  - Angel: Lessons>Extra Credit
  - Due 11:55pm, 31 March
- Observatory open house
  - Fri & Sat, 9:00-11:00pm.
  - MSU Observatory (south of Ag Pavilion)
  - Weather permitting.
- Test 3
  - Tues, 7 April
  - Study guide & practice test
    - Link on syllabus
    - Add Jovian planets
    - Ignore neutron stars & black holes
  - Class of 3/26 (history of low and high-mass stars) is included. Today's class is not included.
- Missouri Club (Show me)
  - Thurs, 7:15-8:15pm
  - room 1420

Pressure in a normal gas

- What is pressure?
  - Think of gas particles in a balloon as baseballs in the balloon.
  - Baseballs move and hit walls of balloon
  - Baseballs push on the balloon.
- Normal gas: PV=nkT
  - Q: Pressure is greater at higher temperature because
    A. Baseballs hitting the walls move faster.
    B. There is less space.
  - Q: Pressure is greater if the volume is smaller because
    A. Baseballs hitting the walls move faster
    B. Baseballs hit the walls more often.



Degeneracy Pressure

- Normal gas
  - P V = n k T
  - Pressure is greater at higher temperature because the marbles are moving faster.
- Degenerate gas
  - If the gas is confined to a very small space, Newton's 2nd law becomes invalid. New laws of motion, called quantum mechanics.
  - Quantum mechanics: Heisenberg's uncertainty relation
    - Speed × space > Planck's constant
    - Baseballs move because they are close together.
    - If you confine an electron to 10^{-8}m, it moves at 70km/s
  - Pressure is not greater at hotter temperature
  - $P V^{5/3} = n^{5/3}$constant. (Pressure does not depend on temperature!)
  - Pressure is greater if gas is confined to smaller region
    - In a smaller star, baseballs move faster
    - Baseballs hit walls faster & more often
    - Pressure is higher

White dwarf

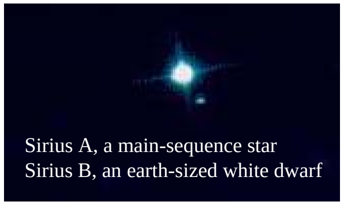
- Electrons in a white dwarf are degenerate.
  - Electrons move because they are close together
- A teaspoon of white dwarf weighs several tons
- How do you get the most cake? Choose the biggest piece.
- How do you get a white dwarf with the most mass? Choose the smallest one.
- A white dwarf with more mass is smaller.
- S. Chandrasekar realized a WD with more than $1.4M_{sun}$ cannot exist. (Its radius is 0.)

End state of the sun is a white dwarf

- In the sun, gravity and pressure are in balance.
- When sun finishes burning H, source of temperature & pressure is gone.
  - Gravity wins; sun shrinks; temperature rises.
  - New fuel. Burn He→C. New source of temperature & pressure. Gravity and pressure are in balance.
- When sun finishes burning He, source of temperature & pressure is gone.
  - Gravity wins; sun shrinks.
  - Degenerate electrons becomes a new source of pressure. Gravity and pressure are in balance without fusing carbon into neon.

- Q Why does the sun end up as a white dwarf?
  a. The sun becomes degenerate.
  b. The sun loses too much mass as a planetary nebula
  c. It takes too long to burn neon.

Black Holes & Neutron Stars



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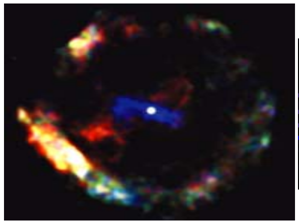
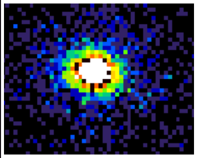


X-ray source G11.2-03
Supernova 386AD
Neutron star in center

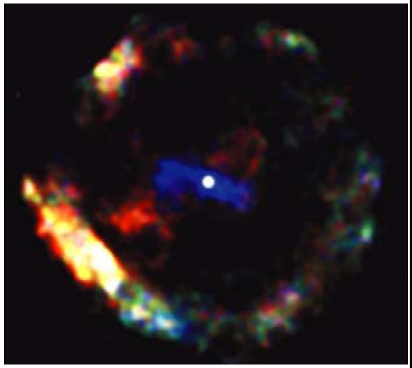


Black hole
Cyg X1

- White dwarfs cannot exist with mass greater than 1.4 $M_{\odot}$. Gravity trumps pressure of degenerate electrons.
- Neutron stars cannot exist with mass greater than 3 $M_{\odot}$. Gravity trumps pressure of degenerate neutrons.
- Nothing can travels faster than light
- Black hole: escape speed exceeds speed of light.

Maximum mass for neutron star

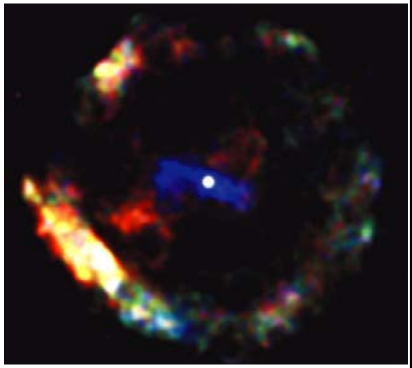
- If pressure is very high, protons and electrons can form neutrons and neutrinos
  - $p + e^{-} + \text{energy} \rightarrow n + \upsilon$
- Neutron star has degenerate neutrons
  - For same speed, pressure is higher b/c neutrons have more mass than electrons.
  - Size of neutron star is kms.
    - Size of WD is thousands of km, size of earth.
- Chandrasekhar: maximum mass for neutron star is $3M_{\odot}$
- If mass is greater, gravity wins. Star collapses; nothing stops collapse.



Supernova in 386AD
X-ray image showing remnant & neutron star.
Fig. 13.6

Maximum mass for neutron star

- Chandrasekhar: maximum mass for neutron star is $3M_{\odot}$
- If mass is greater, gravity wins. Star collapses; nothing stops collapse.
- A main-sequence star or giant with mass > $3M_{\odot}$ can exist.
- A compact (small) object with mass > $3M_{\odot}$ must be a black hole.



Supernova in 386AD
X-ray image showing remnant & neutron star.
Fig. 13.6

Black hole

- Escape from earth
  - To escape from earth's gravity, a molecule must go faster than 11 km/s.
- Escape speed depends on mass and radius
- If mass is big enough or radius is small enough, escape speed is bigger than speed of light.
- If sun were squeezed to 3-km radius, light could not escape from it.
- Schwarzschild radius is boundary between inside & outside.
  - Light can escape if outside Schwarzschild radius.

1. A new compact (not MS, not giant) object is discovered in the sky. Clever astronomers measured its mass to be 2.5 $M_{\odot}$. It cannot be a
   a. NS, BH, or WD
   b. NS, BH
   c. WD
   d. BH

Black hole

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   b. NS, BH
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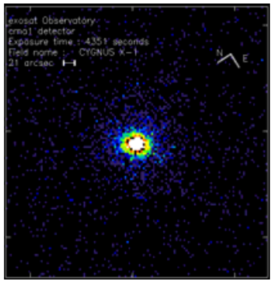
   d. BH <
- How can we detect a black hole if light cannot escape from it?

Black hole

Comis & Kaufmann, Discovering the Universe

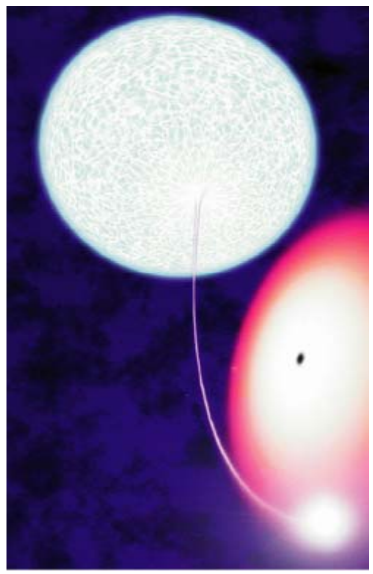


heasarc.gsfc.nasa.gov/ Images/exosat/cygx1.gif

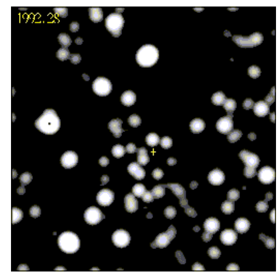
- How can we detect a black hole if light cannot escape from it?
  - Look at something that orbits around it
  - Look at the mass that is falling into it.
- A compact star must be a black hole if its mass is greater than $3M_{\odot}$.
- Cygnus X1
  - Bright source of X rays
  - In visible, star HD226868
  - HD226868 moves around something at 50km/s with 5 day period

Cygnus X1

- HD226868, a giant, donates mass to BH
  - Mass falls toward BH, moves fast, gets hot.
  - Hot gas emits X rays
- Mass of companion
  - Kepler's 3rd law: Radius & period $\Rightarrow$ total mass of two stars.
    - P=5da
    - 5da & 50km/s $\Rightarrow$ R.
  - Speed $\Rightarrow$ mass of companion
  - Mass of companion is $10M_{\odot}$.
- Companion is compact
  - A $10\text{-}M_{\odot}$ star would be seen in visible.

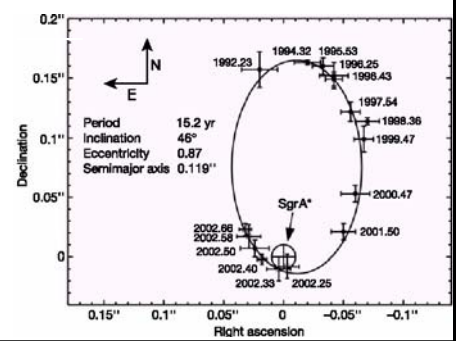


The Black Hole at the the Galactic Center



Infrared observations over 6 years.

Velocities of stars in very center
➔ 1 million $M_{\odot}$ black hole
at position of Sagittarius A^{*}



Q: Chapter 10

1. At the center of the sun, fusion converts hydrogen into ___. (Recall)
2. Fusion in the sun requires a temperature of thousands, millions, billions Kelvin. (Recall)
3. The sun is losing mass because___. (What is the key idea?)
4. The sun will use up its hydrogen in thousands, millions, billions, trillions of years. (Recall)
5. There is more helium in the center of the sun than the surface because__. (What is the key idea?)
6. Will a lead ball will sink to the center of the sun (if it did not melt)? (Recall & ideas about floating.)
7. Does matter move from the center of the sun to the surface? (Recall)
8. Is the sun producing carbon now? ((What is key idea?)
9. What are characteristics of the core, radiation zone, convection zone, photosphere, chromosphere, corona, and solar wind? In which region is Venus? (Recall)
10. If I shine a flashlight toward the sun, would the light go through the corona? (No recall. What is the key information about the corona?)