Life of the Sun—15 Oct

- Energy production in the sun
- Sun will use up the hydrogen in the center in 5Byr
- Center of sun must shrink to get hotter to balance gravity
  - Sun will become a red giant. Surface expands.
- Sun will become a planetary nebula
- Sun will become a white dwarf

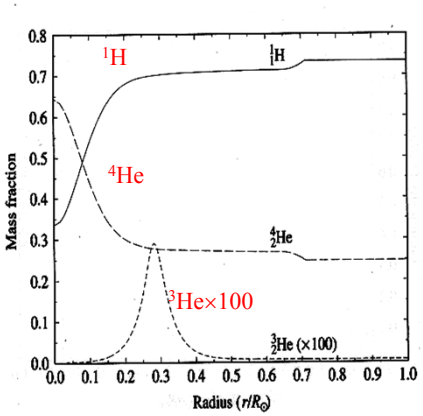
Announcements

- Test 2 is Wed, Oct 20.
  - Covers material though HR diagram of star clusters (11 Oct). Does not cover energy production.
  - Covers homework 5.
  - Mostly on material since first test.
  - One cheat sheet.
  - See practice test on angel.
  - Missouri "Show me" Club
    - Tues, Oct 19, 7:40-8:40pm
    - BPS 1420
- Homework 5 is due at start of class on Mon, Oct 18. No late papers.
- Open house at the MSU Observatory
  - Today and Saturday (October 15 and 16), 9-11pm, weather permitting
  - Bring your friends, parents, siblings, children

Review

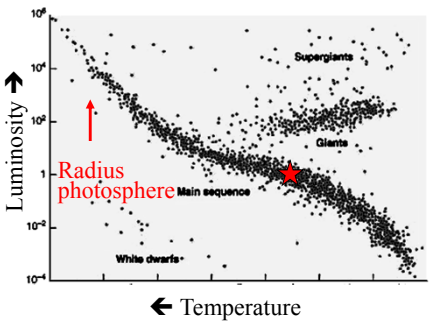
- The sun produces energy by fusing hydrogen into helium $4p \rightarrow {}^4He$.
  - For this to occur, the protons must collide vary fast to overcome the electric repulsion.
  - Repulsion force depends on the product of the charges $Z_1 Z_2$.
    - $Z = 1$ for H
    - $Z = 2$ for He
- Half of the hydrogen in the center is used up.
- For pressure and gravity to balance $\frac{M}{R} = T$
  - Fusion maintains the temperature.

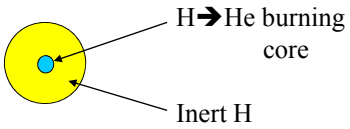
1. If the sun runs out of hydrogen, there is no more fusion to maintain the pressure. What happens?
   A. The sun gets hotter because ___.
   B. The sun gets cooler because ___.



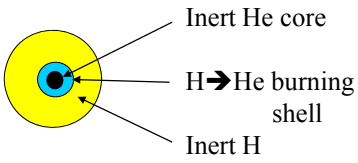
Sun as a main-sequence star

- H→He in the core
- T=15MK
- Fuel will last another 5 Byr.





The sun's choice



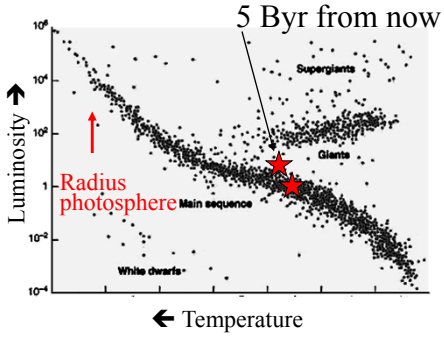
- Sun does a balancing act.

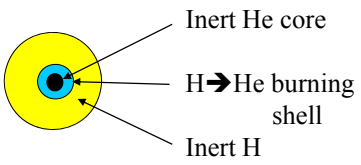
$$\frac{M}{R} = T$$

- Sun must produce energy to replenish the energy radiated away.
- If H→He shuts off, source of energy to maintain pressure shuts off, and gravity wins.
- What does the sun do to adjust for gravity's victory?
- Core of the sun shrinks.
  - Core of sun gets hotter
  - H→He in the a shell surrounding inert core
  - Balance restored.

Sun as a subgiant

- H is gone in the core
- The never-ending battle between gravity and pressure. How does the sun adjust?
  - Without burning fuel to keep temperature up, pressure would fall and gravity would win.
  - Core shrinks, gets hotter
  - H→He in the a shell surrounding inert core
  - Balance restored.

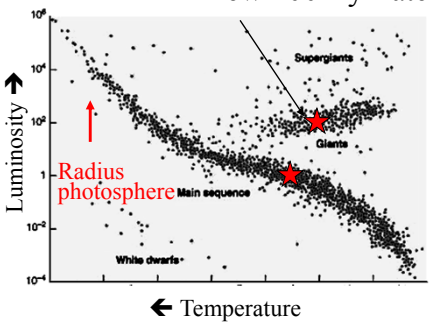


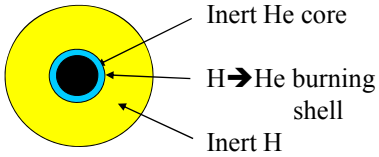


Sun as a giant

A few 100Myr later

- H is gone in the core
- The never-ending battle between gravity and pressure. How does the sun adjust?
  - Without burning fuel to keep temperature up, pressure would fall and gravity would win.
  - Core shrinks, gets hotter
  - H→He in the a shell surrounding inert core
  - Balance restored.
- Inert He core expands

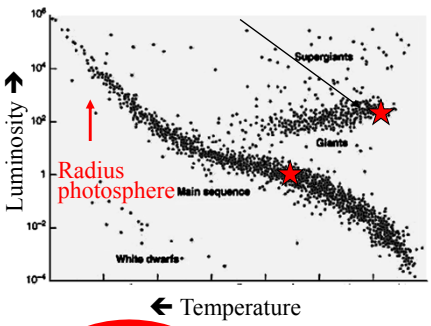


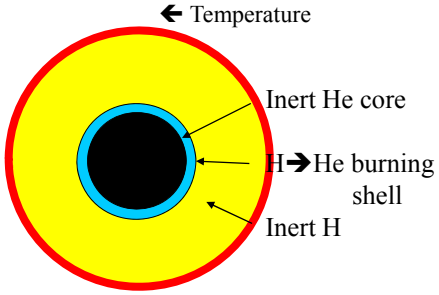


Sun as a giant

Later

- H is gone in the core
- The never-ending battle between gravity and pressure. How does the sun adjust?
  - Without burning fuel to keep temperature up, pressure would fall and gravity would win.
  - Core shrinks, gets hotter
  - H→He in the a shell surrounding inert core
  - Balance restored.
- Inert He core expands





The sun's choice

- Sun does a balancing act.
$$\frac{M}{R} = T$$
- Sun must produce energy to replenish the energy radiated away.
- Without burning fuel to keep temperature up, pressure would fall and gravity would win.
  - Core shrinks, gets hotter T=200MK

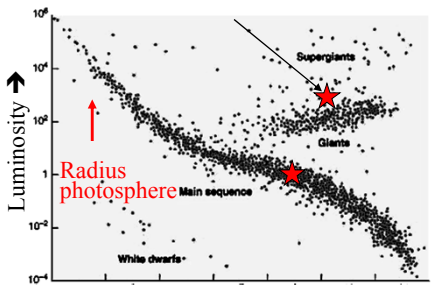
Triple-alpha process

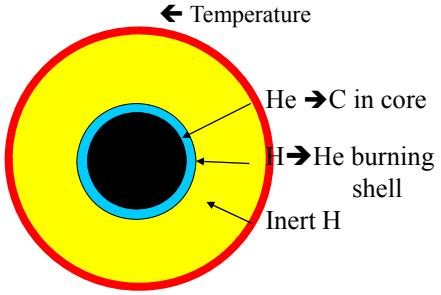
Reaction	Min. Temp.
4 ^{1}H ➔ ^{4}He	10 MK
3 ^{4}He ➔ ^{12}C	200 MK
^{12}C + ^{4}He ➔ ^{16}O, Ne, Na, Mg	800 MK
Ne ➔ O, Mg	1500MK
O ➔ Mg, S	2000MK
Si ➔Fe peak	3000MK

Sun Burns Helium

- H is gone in the core & shell is exhausted
- The never-ending battle between gravity and pressure. How does the sun adjust?
  - Without burning fuel to keep temperature up, pressure would fall and gravity would win.
  - Core shrinks, gets hotter T=200MK
  - 3He→C in the core (triple alpha process)
  - Balance restored.

Later





The sun's choice

1. Why does fusion of helium require a higher temperature?
   A. Helium is heavier
   B. Helium has 2 protons
   C. Helium has two neutrons
- With more charge, it takes higher speeds to bring two He nuclei close enough to fuse.
  - Carbon has 6 protons.

Triple-alpha process

Reaction	Min. Temp.
4 ^{1}H → ^{4}He	10 MK
3 ^{4}He → ^{12}C	200 MK
^{12}C + ^{4}He → ^{16}O, Ne, Na, Mg	800 MK
Ne → O, Mg	1500MK
O → Mg, S	2000MK
Si →Fe peak	3000MK

Other fusion reactions?

- Sun has one more trick after He is exhausted in core.
  - Burn He in a shell
- Sun is not massive enough to shrink further and get hotter
  - Core is supported by pressure of degenerate electrons.
  - Temperature does not rise to burn anything else.
- End of the road: planetary nebula & white dwarf core

Triple-alpha process

Reaction	Min. Temp.
4 ^{1}H → ^{4}He	10 MK
3 ^{4}He → ^{12}C	200 MK
^{12}C + ^{4}He → ^{16}O, Ne, Na, Mg	800 MK
Ne → O, Mg	1500MK
O → Mg, S	2000MK
Si →Fe peak	3000MK

Normal/degeneracy pressure
White dwarfs

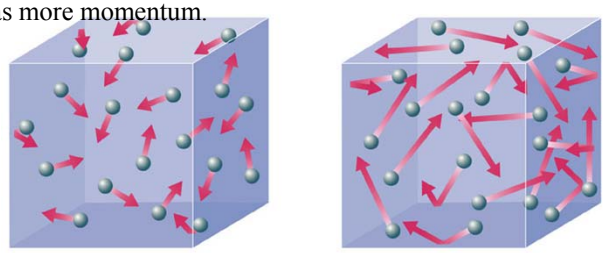
- Pressure on the walls of the box is caused by the gas hitting the walls. Gas transfers momentum to the walls.
- Mental picture: Marbles hit the walls; wall pushes back.
- **Normal gas**

  $P V = n k T$

  $mv^2=kT$

1. Pressure is greater at higher temperature because ___. I. more marbles are hitting the wall every second. II. the marbles are moving faster and each marble has more momentum.

   A. I only
   B. II only
   C. I & II



Longer arrows mean higher average speed.

Pressure in a "degenerate gas"

- **Normal gas**

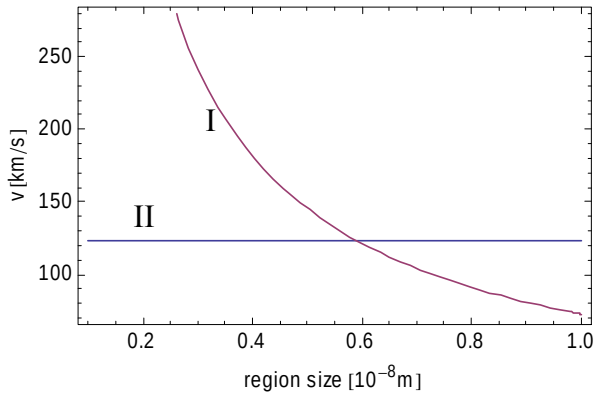
  $P V = n k T$

  - Pressure is greater at higher temperature because the marbles are moving faster. $mv^2=kT$
- **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, apply.
- Heisenberg's uncertainty principle. Suppose a particle is allowed to move within a region of length x.

  $m v x > h$

  momentum x > h

  v is speed. h is Planck's constant.
  - A particle must move if it is confined to a small space.
  - If you confine an electron to 10^{-8}m, it moves at 70km/s.



1. Plot shows the speed of a normal gas made of electrons with a temperature of 1000K and a degenerate gas of electrons with a temperature of 0K.
   A. I is a NG. II is a DG.
   B. I is a DG. II is a NG.

Pressure in a "degenerate gas"

- **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, apply.
- Heisenberg's uncertainty principle. Suppose a particle is allowed to move within a region of length x.
  m v x > h
  momentum x > h
  v is speed. h is Planck's constant.
  - A particle must move if it is confined to a small space.
  - If you confine an electron to 10^{-8}m, it moves at 70km/s.
- Pressure of a degenerate gas
  - $P V^{5/3}$ = constant $n^{5/3}$
  - constant = h^2/m
  - Pressure does not depend on temperature!!!
- End state of the sun
  - Without any energy production, the sun would normally shrink because gravity wins.
  - However, degeneracy pressure balances gravity. The sun is stable and cannot shrink.