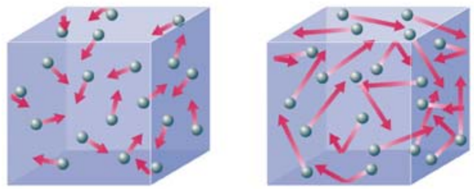
Normal/degeneracy pressure
White dwarfs — Oct 10

- 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

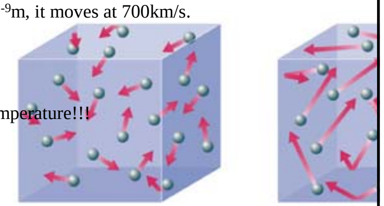
1. Pressure is greater at higher temperature because
   A. more marbles are hitting the wall
   B. the marbles are moving faster
2. If n is greater, the pressure is greater because



Longer arrows mean higher average speed.

Degeneracy pressure

- Normal gas
  - P V = n k T
  - Pressure is greater at higher temperature because the marbles are moving faster.
- If the gas is confined to a very small space, Newton's 2nd law becomes invalid. New laws of motion, called quantum mechanics.
- Heisenberg's uncertainty principle. A particle is allowed a space x.
  - The quantity m v x must be greater than h, Planck's constant.
  - A particle must move if it is confined to a small space.
  - If you confine an electron to 10^{-9}m, it moves at 700km/s.
- Pressure of a degenerate gas
  - $P V^{5/3}$ = constant $n^{5/3}$
  - constant = h^2/m
  - Pressure does not depend on temperature!!!



Longer arrows mean higher average speed

Other fusion reactions?

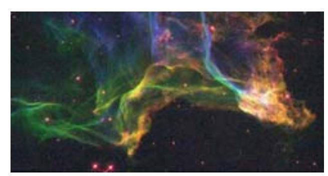
- Sun has one more trick after He is exhausted in core.
  - Burn He in a shell
- Sun is not massive enough to shrink further and get hotter
  - Core is supported by pressure of degenerate electrons.
  - Temperature does not rise to burn anything else.
- End of the road: planetary nebula & white dwarf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

Triple-alpha process

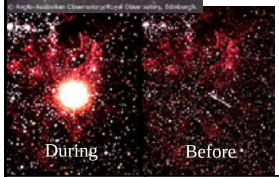
Reaction	Min. Temp.
4 ^1H → ^4He	10 MK
3 ^4He → ^{12}C	200 MK
^{12}C + ^4He → ^{16}O, Ne, Na, Mg	800 MK
Ne → O, Mg	1500MK
O → Mg, S	2000MK
Si →Fe peak	3000MK

Supernovae — Oct 10

- Where were the elements in the baby made?
  - Carbon was made and expelled by giants
  - Iron was made in massive stars and expelled by supernovae
  - Heavier elements were made in supernovae & in giants by the R & S processes

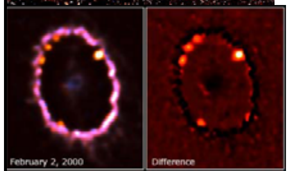


Cygnus Loop
Supernova 20,000 yr ago

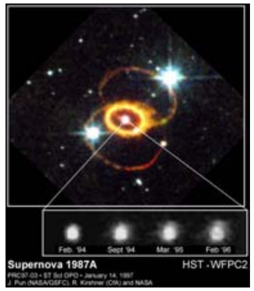


Supernova 1987A

- Exploded in Large Magellanic Cloud
  - LMC is small galaxy that orbits our own Milky Way Galaxy.



Pre-existing circumstellar ring lit up first by photons from SN, now by blast wave from SN.



Guest star of 1054

- Records of Sung Dynasty
  - In the first year of the period Chih-ho, …, a guest star appeared several degrees SE of Thien-kuan. After more than a year it gradually became invisible.–p578.
- Gas expelled in 1054AD, still glowing
- Other SN
  - 1572 Tycho
  - 1604 Kepler

Supernova remnants

We expect one supernova in Milky Way every 25-100 yrs.

Crab
1,000 yrs old

Cygnus Loop
20,000 yrs old.
2500 LY away.

IC 443
8000 yrs old

Supernovae

- Explosion releases enormous energy
- Luminosity in photons temporarily exceeds that of whole galaxy full (100 billion) of stars.

What is a supernova? Why sun becomes a white dwarf, not a supernova

- In future double-shell burning sun, hot enough to burn
  $3\,^4\text{He} \rightarrow \,^{12}\text{C}$
- When He exhausted, gravity wins, and core contracts.
- Temperature rises.
- Electrons are so tight that they become degenerate.
- New source of pressure to resist gravity.
- Temperature not hot enough to burn carbon.

Reaction	Min. Temp.
$4\,^1\text{H} \rightarrow \,^4\text{He}$	10^7 ° K
$3\,^4\text{He} \rightarrow \,^{12}\text{C}$	2×10^8
$^{12}\text{C} + \,^4\text{He} \rightarrow \,^{16}\text{O}$, Ne, Na, Mg	8×10^8
Ne → O, Mg	1.5×10^9
O → Mg, S	2×10^9
Si → Fe peak	3×10^9

What is a supernova? Why massive star becomes a supernova

- In future double-shell burning massive star, hot enough to burn
  $3\,^4\text{He} \rightarrow \,^{12}\text{C}$
- When He exhausted, gravity wins, and core contracts.
- Temperature rises by larger amount b/c gravity is stronger.
- Temperature hot enough to burn carbon.
  $^4\text{He} + \,^{12}\text{C} \rightarrow \,^{16}\text{O}$, etc

Reaction	Min. Temp.
$4\,^1\text{H} \rightarrow \,^4\text{He}$	10^7 ° K
$3\,^4\text{He} \rightarrow \,^{12}\text{C}$	2×10^8
$^{12}\text{C} + \,^4\text{He} \rightarrow \,^{16}\text{O}$, Ne, Na, Mg	8×10^8
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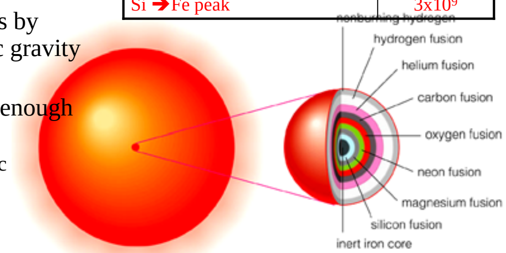

What is a supernova? Why massive star becomes a supernova

- Hot enough to burn
  $^4\text{He} + \,^{12}\text{C} \rightarrow \,^{16}\text{O}$, etc
- When C exhausted, gravity wins, and core contracts.
- Temperature rises.
- Temperature hot enough to burn neon.
  $^{20}\text{Ne} + \,^4\text{He} \rightarrow \,^{24}\text{Mg}$
- Disaster with iron
  - Burning releases energy
  - Fusing iron takes up energy
- Gravity finally wins.

Reaction	Min. Temp.
$4\,^1\text{H} \rightarrow \,^4\text{He}$	10^7 ° K
$3\,^4\text{He} \rightarrow \,^{12}\text{C}$	2×10^8
$^{12}\text{C} + \,^4\text{He} \rightarrow \,^{16}\text{O}$, Ne, Na, Mg	8×10^8
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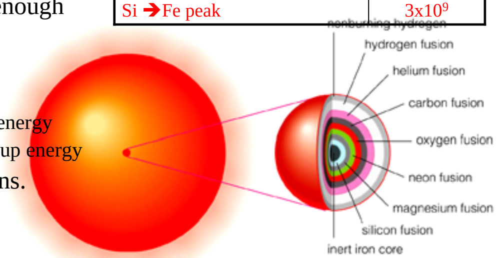

What is a supernova? Why massive star becomes a supernova

- Disaster with iron
  - Burning releases energy
  - Fusing iron takes up energy
- Gravity finally wins.
- Star collapses in few seconds
- Rebounds as supernova
  - Reason for rebounding is topic of current research
- Expel outer layers

Reaction	Min. Temp.
$4\,^1\text{H} \rightarrow \,^4\text{He}$	10^7 ° K
$3\,^4\text{He} \rightarrow \,^{12}\text{C}$	2×10^8
$^{12}\text{C} + \,^4\text{He} \rightarrow \,^{16}\text{O}$, Ne, Na, Mg	8×10^8
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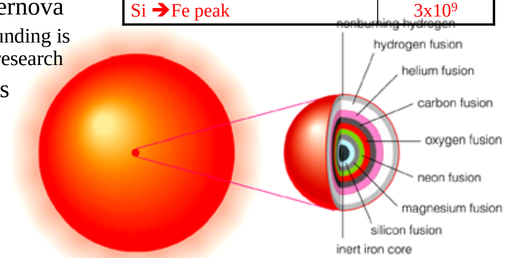
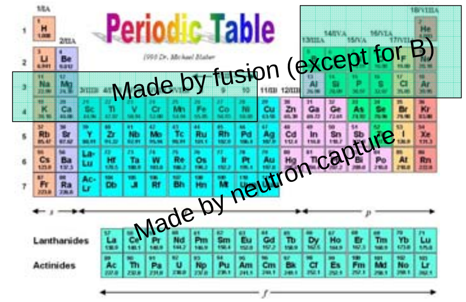


What is left?

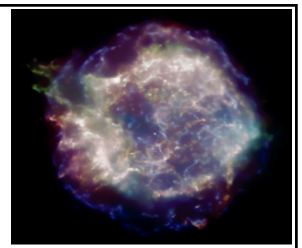
- Outer layers expelled into space. New stars may form.
- Core becomes
  - Neutron star. One in Crab. Pulses every 1/30 s.
  - Black hole
- Neutron star
  - Normally neutron→proton+electron+neutrino+energy
  - Pressure is so high that proton+electron+energy→neutron+neutrino
  - Whole star is like a big nucleus of neutrons.
  - Neutrons are degenerate
  - Star is size of Lansing

Making elements heavier than iron

- Lighter elements (He, O, C, Ne, Mg, etc) are made by fusion with a release of energy
  - $4H \rightarrow He$ + energy
  - $3He \rightarrow C$ + energy
- Fe+He→ (heavier element)   requires energy. No go.



Neutron capture



- In a supernova, there are free neutrons made by destroying nuclei.
- Nucleus captures neutrons and turns into a heavier nucleus.
- Nucleus may decay into a more stable one.
- Nucleus may capture more neutrons.
- Eventually unstable nuclei decay into stable ones. Some heavy as uranium

- Calculation of nuclear reactions in a supernova.
- Start with iron and add neutrons
- Look at gold
  - 79 protons, 197-79=118 neutrons

Questions on the Supernova Movie

1. What is the only element at the start? How many neutrons does it have?
2. At what time did some gold form? Gold has 79 protons. Is this gold stable?
3. At the end of the calculation, how many protons does the nucleus with the most protons have?
4. What is the time at the end of the calculation?
5. Are the end products stable?

- “R process movie” at www.jinaweb.org/html/gallery3.html

Where were the elements in the baby made?

- Lighter elements (He, O, C, Ne, Mg, etc) are made by fusion with a release of energy
  - 4H → He + energy
  - 3He → C + energy
- Elements heavier than iron are made in supernovae and in gian