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

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 \( 10^{-9} \text{m} \), it moves at \( 700\text{km/s} \).
• Pressure of a degenerate gas
  • \( P V^{5/3} = \text{constant} \ n^{5/3} \)
  • constant = \( h^2/m \)
• Pressure does not depend on temperature!!!

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

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Min. Temp.</th>
</tr>
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<tbody>
<tr>
<td>( ^4\text{He} \rightarrow ^{16}\text{O} )</td>
<td>800 MK</td>
</tr>
<tr>
<td>( ^1\text{H} + ^4\text{He} \rightarrow ^3\text{He} \rightarrow ^4\text{He} )</td>
<td>200 MK</td>
</tr>
<tr>
<td>( ^2\text{He} + ^4\text{He} \rightarrow ^8\text{O}, ^{12}\text{C} )</td>
<td>300 MK</td>
</tr>
<tr>
<td>( ^{12}\text{C} + ^4\text{He} \rightarrow ^7\text{Li} )</td>
<td>10 MK</td>
</tr>
<tr>
<td>( ^{12}\text{C} + ^4\text{He} \rightarrow ^7\text{Be} )</td>
<td>50 MK</td>
</tr>
<tr>
<td>( ^{12}\text{C} + ^4\text{He} \rightarrow ^7\text{Be} )</td>
<td>70 MK</td>
</tr>
<tr>
<td>( ^{12}\text{C} + ^4\text{He} \rightarrow ^7\text{Be} )</td>
<td>90 MK</td>
</tr>
<tr>
<td>( ^{12}\text{C} + ^4\text{He} \rightarrow ^7\text{Be} )</td>
<td>110 MK</td>
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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
- Crab
  - 1,000 yrs old

- Cygnus Loop
  - 20,000 yrs old

- 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 \( ^3\text{He} \rightarrow ^{12}\text{C} \).
- 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.

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</tr>
<tr>
<td>( ^3\text{He} \rightarrow ^{12}\text{C} )</td>
<td>( 2 \times 10^9 )</td>
</tr>
<tr>
<td>( ^{12}\text{C} + ^3\text{He} \rightarrow ^{16}\text{O}, ^{10}\text{Ne}, ^{11}\text{Na}, ^{12}\text{Mg} )</td>
<td>( 8 \times 10^9 )</td>
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<tr>
<td>Ne ( \rightarrow ^{16}\text{O}, ^{10}\text{Ne}, ^{11}\text{Na}, ^{12}\text{Mg} )</td>
<td>( 1.5 \times 10^{10} )</td>
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<tr>
<td>O ( \rightarrow ^{16}\text{O}, ^{10}\text{Ne}, ^{11}\text{Na}, ^{12}\text{Mg} )</td>
<td>( 2 \times 10^9 )</td>
</tr>
<tr>
<td>Si ( \rightarrow ^{28}\text{Si} )</td>
<td>( 3 \times 10^8 )</td>
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What is a supernova? Why massive star becomes a supernova

- Hot enough to burn \( ^4\text{He} + ^{12}\text{C} \rightarrow ^{16}\text{O}, \text{etc} \).
- 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.

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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 → He + energy
  • 3He → 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?

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
  - $4\text{H} \rightarrow \text{He} + \text{energy}$
  - $3\text{He} \rightarrow \text{C} + \text{energy}$
- Elements heavier than iron are made in supernovae and in giant stars:
  - Made by fusion (except for B)
  - Made by neutron capture

Periodic Table:

- Made by fusion (except for B)
- Made by neutron capture

Locations:
- Actinides
- Last actinides